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Habitat affinity analysis as a tool to guide environmental restoration for an imperiled estuarine fish: the case of the delta smelt in the Sacramento-San Joaquin Delta

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ABSTRACT

Habitat restoration efforts in the Sacramento-San Joaquin Delta in central California move forward under the state's ambitious Bay Delta Conservation Planning process, despite a paucity of information on the habitat needs of many of the plan's targeted species. The endemic delta smelt, protected as threatened under the federal Endangered Species Act, is a primary focus of those efforts despite key uncertainties regarding many aspects of its relationship with the estuary's physical and biotic resources. Here we carry out habitat affinity analysis for multiple life stages of the delta smelt drawn from time-series data from four trawl surveys, and data on environmental attributes taken from throughout the distribution of the fish. Ranges of conditions acceptable to delta smelt for each of seven environmental attributes were identified. Low turbidity and high water temperatures render a large portion of the estuary seasonally unacceptable to delta smelt. Within areas that experience largely acceptable water quality conditions, patterns of delta smelt occurrences indicate that habitat occurs where deep channels adjoin shallow-water circumstances and extensive patches of emergent vegetation. Habitat suitability indices show that favored environmental circumstances vary with life stages, and delta smelt move as they mature to access suitable areas with environmental attributes in acceptable ranges. Areas that exhibit highest geometrically weighted average HSI values for environmental attributes are displayed on maps, and can be viewed as representing potential priority target areas for habitat restoration efforts. Delta smelt should benefit in priority target areas with channel modification and directed wetlands restoration efforts.

INTRODUCTION

It's hardly the only venue where institutional commitments to environmental restoration are outpacing the reliable knowledge to guide it. But ecological information essential to realizing the ambitious Bay Delta Conservation Plan (BDCP) is in distinctly short supply. Federal and state resources agencies have combined to conserve ecological communities and dozens of at-risk species in the Sacramento-San Joaquin Delta and estuary in central California in seeking to reverse a century and a half of ecosystem alteration (BDCP 2012). Absent direct observation of the fishes of concern in the estuary's murky waters, and with monitoring and surveys largely lacking experimental design, management planners enjoy few insights from ecological assessments -- save confirmation that the estuary's ecosystems are dynamic and highly disrupted (see Healey 2008). The contemporary estuary is among the most altered aquatic ecosystems in the United States (Nichols et al. 1986). It has suffered the loss of more than 95% of its historic tidal wetlands; its shallow freshwaters, riparian communities, and floodplains have been lost to levees, hard channels, urbanization, and agriculture (Thompson 1957). Estuary inflows during spring months in high-flow years are now less than what they would be absent upstream reservoirs and water diversions, while flows through the estuary in the autumn are often greater (CDWR 2007). More than 200 non-native plant and animal species have become established and dominate nearly all of the estuary's ecological communities (URS 2007). Dozens of contaminants have accumulated in substrates and continue to be delivered to the waters of the system (Healey 2007). All the while federal and state wildlife agencies, focused on their legal mandates to protect individual at-risk species, it seems, have failed to protect those species or restore the estuarine system and some version of its natural biodiversity (Norgaard et al. 2009).

With its commitment to California's Natural Communities Conservation Planning Act, the BDCP addresses biodiversity at an ecological community and landscape scale. But, the program's central initiative is the delivery of take permits for the estuary's many protected species. Accordingly, the essential pathway to conservation success will be through the recovery of individual species that have suffered declines in numbers such they have been found to warrant protection under the federal and California Endangered Species Acts. The conservation plan will be considered successful upon restoration of the habitats that support those species. Better-informed, species-focused conservation efforts have demonstrated some progress in the greater planning area; for example, the restoration of riparian and other terrestrial communities along the major tributaries that feed the Delta have benefitted listed bird and amphibian species (Faber 2003). But, little evidence of headway can be found in efforts to rehabilitate the Delta's highly degraded aquatic systems. This situation is linked in part to the dismal state of knowledge of the ecology of the system's flagship species, the delta smelt. Indeed, the delta smelt, a small, transparent euryhaline fish species with a mostly annual life cycle found in turbid waters of the Delta (Bennett 2005), may be among the least well-understood species protected under the federal Endangered Species Act. Nearly two decades after federal protection was conferred to the delta smelt, much of its basic ecology and behavior is still inferred – indeed delta smelt have never even been observed to reproduce in nature – and the relative importance of factors that threaten its persistence and recovery are the subject of active debate. The proposed restoration of habitat for delta smelt -- a primary target of the BDCP's multispecies, multi-decadal, multibillion-dollar conservation effort -- is hampered by a salient shortcoming. No generally accepted description of its habitat exists.

To address that shortcoming, and, at the same time, to offer at least contingent guidance to agency managers charged with constructing, restoring, and rehabilitating habitat for delta smelt, we have taken a novel approach to applying "habitat affinity analysis" in conservation planning. We have used not-uncommonly employed habitat suitability indices (http://el.erdc.usace.army.mil/emrrp/emris/emrishelp3/list_of_habitat_suitability_index_hsi_models_pac.htm) in an effort to parameterize descriptions of the direct and indirect effects and influences of physical and biotic attributes of the estuary on delta smelt. Here we draw from publically available trawler-based survey data on the distributions and relative abundances of multiple life stages of the delta smelt that are derived from samples. Demographic data on delta smelt from survey stations are related to data available on environmental attributes of the estuary and bathymetric data derived from USGS databases to infer landscape characteristics that may contribute to delta smelt habitat. We endeavor to inform habitat restoration for delta smelt by following a sequence of steps.

First, drawing on agency-generated conceptual models that articulate hypothesized relationships between delta smelt and environmental variables, including stressors in the estuary (see Armor et al. 2005, Baxter et al. 2007, Nobriga and Herbold 2009), we identify candidate environmental attributes that appear to contribute to the extent and quality of habitat for delta smelt. Second, we use affinity analyses -- that is, we compare the frequency of resource use by, or co-occurrence with, delta smelt to resource availability -- to identify which environmental attributes determine the distribution of delta smelt at each life stage. Third, we utilize the results of the affinity analyses to develop suitability indices for each deterministic attribute separately, and then combine the suitability indexes to derive numerical meta-indices of aggregated habitat quality for each life stage using multiple regression analysis. The approach permitted us to identify the specific environmental attributes that are relevant to delta smelt when several are considered simultaneously in a comprehensive treatment of its habitat. Having identified important habitat attributes, we are able to determine the environmental factors that are lacking or appear to fall out of the range of acceptable conditions for delta smelt, and where those circumstances occur, in support of efforts to inform potential restoration projects.

Carrying out these steps we find it possible to offer substantive guidance to conservation planners working in the Delta. The results of our analyses offer prescriptions on (at least) two spatial scales. First, delta smelt distribution data mapped on three physical variables indicate that broad geographic portions of the contemporary estuary may not be appropriate targets for mechanical habitat restoration efforts because one or more physical variables, which are not under management control, fall outside ranges acceptable to delta smelt. Efforts to restore habitat structure and function in those locations are not likely to result in the (re)establishment of, or increased productivity by, delta smelt. Second, in situations not so constrained, the mapped habitat-affinity relationships that we have generated can be used to identify locations that are suitable targets for restoration and assist in identifying the mechanical habitat enhancing actions that might contribute to supporting delta smelt.

We suggest that the approach offered here might be applied in other conservation planning circumstances where focal species may not be ecologically well understood, where species-habitat relationships are uncertain, and where there is an urgent need to identify and implement effective environmental restoration projects with constrained resources and limited opportunities.

METHODS

Study system

The San Francisco Estuary is the largest of its kind along the U.S. Pacific Coast (Rosenfield and Baxter 2007). Formed by the confluence of the Sacramento and San Joaquin watersheds, the estuary drains nearly 40% of California's surface area (van Geen and Luoma 1999, Sommer et al. 2007). The estuary is tidally influenced, with fresh river water from the east mixing with saline ocean water from the west. The major water bodies within the estuary include the Sacramento-San Joaquin Delta (Delta), which lies east of the confluence of the Sacramento and San Joaquin rivers, Suisun Bay, Carquinez Strait, and the Napa River, as well as San Pablo and San Francisco bays to the west (Figure 1). The internal estuary is highly altered from its pre-settlement physiognomy, existing now as a network of mostly fortified waterways surrounding a patchwork of subsided islands behind earthen levees. The extensive marshlands that previously dominated the estuary and floodplains that surrounded it have largely been replaced by cultivated agriculture.

Two native fishes – the Sacramento perch (*Archopilites interruptus*) and thicktail chub (*Gila crassicauda*) – vanished with the post-Gold Rush settlement, conversion, and utilization of the estuary as extensive tule-dominated wetlands dissected by dendritic channels of widely varying dimensions and subject to complex tidal currents were diked and dredged. The estuary now supports a limited assemblage of native fishes; some are resident, some are anadromous transients, and several are endemic, notably the federally protected delta smelt. But the delta smelt and the rest of the native fishes now exist in communities dominated by non-native competitors and predators, supported by a highly altered food web and a local absence of essential habitat-defining environmental features and resources. Against that background, resource managers in the San Francisco estuary are challenged to identify conservation actions that will contribute to sustaining an imperiled native fishery and contribute to the recovery of listed species from strong inferences of those species ecological relationships and habitat needs.

Candidate habitat attributes

We began by developing a list of candidate environmental attributes that previously had been observed or surmised to potentially contribute to habitat quality for estuarine fish. These include turbidity, salinity, temperature, dissolved oxygen, pH, aquatic vegetation, prey density, water depth, substrate composition, and the extent of adjoining marshlands (see Pardue 1983, Weinstein 1986, Stier and Crance 1985, Brown et al. 2000 for lists). Environmental factors that are suspected to affect delta smelt are only slightly more limited in number (Armor et al. 2005, Baxter et al. 2005, Bennett 2005, and Nobriga and Herbold 2009 for conceptual models and natural history syntheses). Three standard water quality factors, temperature, salinity and turbidity have been hypothesized to affect habitat quality (Feyrer et al. 2007, Nobriga et al. 2008). Water temperature has an influence on spawning (Wang 1986, Meng and Matern 2001, Bennett 2005, Feyrer 2004, Grimaldo et al. 2004, Sommer et al. 2004), embryo survival (Moyle 2002, Mager et al. 2004), available habitat during the summer (Nobriga et al. 2008), and adult survival (Swanson et al. 2000). Hieb and Fleming (1999) suggest that delta smelt are found across a near estuary-wide range of salinity conditions. It has been asserted that delta smelt prefer turbid water, perhaps for successful feeding (Baskerville-Bridges et al. 2004, Mager et al. 2004), and because it may reduce susceptibility to predation.

Investigators have described the calanoid copepod prey that support delta smelt (Lott 1998, Nobriga 1998 and 2002). Two multivariate analyses of an array of environment attributes of the Delta identified prey abundance as the primary determinant of population dynamics in delta smelt (Maunder and Deriso 2011, Miller et al. 2012). The fish is often described as frequenting shoals adjacent to deeper channels (Moyle 2002), with an assumption that emergent wetlands contribute to productivity at the base of the food web that supports the delta smelt. Hobbs et al. (2006) linked superior nursery conditions to increased feeding success; and other studies have recognized the potential importance of fish access to wetlands and floodplains (see Lindberg and Marzula 1993, McIvor and Brown 1999). Moyle et al. (1992) indicate that spawning occurs near estuary and river shorelines and adjoining sloughs. Substrate composition may be important in determining spawning habitat (Moyle 2002). McGowan (1998) and McGowan and Marchi (1998) found that areas inhabited by the invasive water-weed *Egeria densa* are not typically inhabited by native fish in the estuary, including delta smelt, and that low abundance of delta smelt is generally associated with areas supporting higher concentrations of submerged aquatic vegetation of all types (see also Nobriga et al. 2005, Grimaldo et al. 2009). Lehman et al. (2010) document low delta smelt abundances in areas subject to episodic blooms by the toxic blue-green alga *Microcystis.*

From the preceding sources, we developed and organized a list of candidate environmental attributes for consideration in habitat affinity analyses for delta smelt (Table 1).

Table 1. *Candidate habitat attributes that may affect the distribution and abundance of delta smelt.*

Aquatic/hydraulic attributes of delta waters

1. Physical water-quality properties (turbidity, salinity, temperature)
2. Chemical water-quality properties (dissolved oxygen, pH)
3. Presence, concentration, absence of contaminants
4. Flow velocity

Biological attributes of the estuary

1. Prey availability (types and densities of food source items)
2. Predation pressure
3. Areal extent, type, and density of aquatic vegetation
4. Presence of *Microcystis*

Physical attributes of the estuary

1. Type of water body
2. Depth of channel/water body
3. Width of channel/water body
4. Extent of proximate shallow water
5. Substrate structure and composition (grain size, organic content)
6. Distance to wetlands

Data Sources and Treatment

Fish surveys -- A synthetic description of habitat for delta smelt must consider suites of environmental attributes and thresholds that act on its individual life stages. Habitat extent and quality, and the geographic location of habitat may vary between life stages; concomitantly, different sites within the estuary may be suitable or unsuitable for the fish at different stages in its life cycle. The California Department of Fish and Game carries out multiple surveys of Delta fishes, returns from which include delta smelt in temporal samples that span its annual life cycle. Surveys include the 20 mm Survey, Summer Tow-net Survey (STN), Fall Midwater Trawl (FMWT), and Spring Kodiak Survey, which sample extensive areas of the Delta and collect delta smelt in meaningful numbers. The methods for these surveys have been documented previously (Moyle et al. 1992, USFWS 2004, Bennett 2005); the varying strengths and weaknesses of several of these surveys as population assessment tools for delta smelt have been discussed in detail by Bennett (2005). We used data from these publicly available fish surveys, delineating life stages as depicted in Table 2, to assess the distribution in local densities of delta smelt. We utilized data from consistently surveyed stations; that is, stations that were surveyed in every year, or in every year but one since 1995, to ensure multiple observations at sites. The time period represented for each life stage reflects the months when that life stage typically predominates among sampled delta smelt. On average, more than 75% of individuals from a given life stage were sampled during the temporal windows presented. Because year-to-year variation exists in the timing of the appearance of each life stage, we considered the period during which 90% of the specific life-stage was sampled. Doing so, we excluded the temporal extremes when habitat attributes and delta smelt presence are less certain due to the very small numbers of individuals sampled. For the FMWT, however, we considered only the months of September and October, rather than the full period of the survey through December, because the first two months of the trawl period had been identified by CDFG as the basis for regulatory decisions.

Table 2. *Delineation of life stages used to examine delta smelt affinity for habitat attributes. Monitoring program data used for each life stage description (either fish length or reproductive stage), and months and years of sampling data used in our study are described. Gonadal stages of male and female delta smelt found in spring Kodiak Trawl database were classified by CA Department of Fish and Game (CDFG) following Mager (1986). Descriptions of reproductive stages are available at http:/www.dfg.ca.govdelt/data/skt/eggstages.asp*

	Sub-juveniles	Juveniles	Juveniles	Sub-adults	Mature Adults: Pre-spawning	Mature Adults: spawning
Monitoring Program	20-mm	20-mm	STN	FMWT	Kodiak	Kodiak
Life Stage Distinction	≥ 15, <30mm	30-55 mm	30-55 mm	> 55 mm	Reproductive stages: females 1-3, males 1-4	Reproductive stages: females 4, males 5
Time Period	May-Jun	Jun-Jul	Jun-Aug	Sep-Oct	Jan-Feb	Mar-Apr
Years of data used in this study	1995-2009	1995-2009	1967-2009	1967-2009	2002-2009	2002-2009

Covariate Specification -- In order to assess the relative influence of local and regional environmental factors that operate to determine delta smelt occurrences, we considered habitat associations at two spatial scales -- site and regional. At the site scale we addressed covariates using data drawn from individual monitoring stations – either as data collected that were taken along with fish samples (temperature, salinity, and turbidity), or as geographic and bathymetric data drawn from geographic areas adjacent to those stations (depth, area of shallows, channel width, distance to wetlands). Additionally, we collected data on substrate composition in March 2010 at stations where water depth was less than 7 meters, classifying substrates using delineations in Table 3. At the regional scale we considered factors that operate at broader spatial scales (including water body type, prey availability, and predation pressure). Specification of these attributes is provided in Table 3.

Table 3. *Specification of covariates and sources of data for the affinity analyses.*

Attribute	Method of measurement or category list	Source description or derivation
Turbidity	Secchi depth (cm)	IEP[1] Monitoring Programs
Salinity	Electrical Conductivity (Ec)	IEP[1] Monitoring Programs
Temperature	Degrees Celsius	IEP[1] Monitoring Programs
Water body type	Bay-Shoal	Station in a bay overlying a shoal
	Bay Channel	Station in a bay overlying a channel >5 m deep
	River Channel	Station on the Sacramento, San Joaquin or Mokelumne Rivers upstream from their confluence
	Slough	Station on a predominantly anthropogenic, tidally influenced channel
Depth	Average depth within 1 km of station	http://sfbay.wr.usgs.gov/sediment/sfbay/downloads.html http://sfbay.wr.usgs.gov/sediment/delta/downloads.html
Width	Water body width (meters)	GIS (ArcInfo) calculated water body width (meters) based on water boundaries digitized from aerial imagery perpendicular to flow.
Area of shallow water	Area of water less than 2 meters deep within 1 km of station	http://sfbay.wr.usgs.gov/sediment/sfbay/downloads.html http://sfbay.wr.usgs.gov/sediment/delta/downloads.html
Substrate composition (categories)	Rip-rap	>3/4 rip-rap, <1/3 vegetated over
	Cobble-gravel	<3/4 rip-rap, <1/3 vegetated cover, cobble-gravel dominant
	Sand	<3/4 rip-rap, <1/3 vegetated cover, sand dominant
	Mud	<3/4 rip-rap, <1/3 vegetated cover, mud dominant
	Organic	<3/4 rip-rap, <1/3 vegetated cover, organic material dominant
	Algal	>1/3 vegetated cover, algae dominant
	Rooted Vascular	>1/3 vegetated dominant, rooted vascular dominant
Prey density	Density (#/m^3) of juvenile calenoid copepods for the 20mm survey, or adult calenoid copepods for other surveys, at the nearest zooplankton survey station within 5 km of an IEP station	IEP Zooplankton Survey
Distance to wetlands	Distance in meters to tidal estuarine emergent wetlands greater than 100 ha	http://www.fws.gov/wetlands/Data/DataDownload.html http://www.dfg.ca.gov/biogeodata/gis/veg.asp (California Central Valley Wetlands and Riparian GIS, published 1997, processed from 1992-93 data)

[1] The Interagency Ecological Program is a long-standing multi-institutional consortium of state and federal water resources and wildlife agencies that carry out research and monitoring on the estuary's environmental resources. (see -- http://www.water.ca.gov/iep/)

IEP Monitoring Programs -- 20mm Survey: ftp://ftp.dfg.ca.gov/Delta%20Smelt/
http://www.dfg.ca.gov/delta/projects.asp?ProjectID=20mm

Summer Townet Survey
http://www.dfg.ca.gov/delta/projects.asp?ProjectID=TOWNET

Fall Midwater Trawl
http://www.dfg.ca.gov/delta/projects.asp?ProjectID=FMWT

Spring Kodiak Trawl: ftp://ftp.dfg.ca.gov/Delta%20Smelt/
http://www.dfg.ca.gov/delta/projects.asp?ProjectID=SKT

Zooplankton Study
http://www.dfg.ca.gov/delta/projects.asp?ProjectID=ZOOPLANKTON

Not unexpectedly, upon investigating data availability, we found insufficient data to support the inclusion of some variables in the affinity analyses. Specifically we were unable to obtain suitable data on dissolved oxygen, pH, contaminants, velocity, predation pressure, aquatic vegetation, or presence of *Microcystis* in a regular spatial and temporal frame. Data on some of these variables do exist, but not in time series or in data sets that cover the geographic range of delta smelt.

Affinity Analyses

Affinity analysis compares the availability of an environmental resource, or physical characteristic or its condition, with the use of that resource or co-occurrence with that physical characteristic by a species of interest (Lechowitz 1982, Grost et al. 1990, Monaco et al. 1998, Cardona 2006). When little is known about a species, an affinity analysis can offer insights into the nature of the relationship between an environmental attribute and the target species, depending on whether the species exhibits an affinity with or aversion to the environmental attribute, and whether an affinity, if found, is strong or weak. It does not require the *a priori* specification of a functional ecological relationship; therefore, it does not presuppose the nature of the relationship that may exist. Graphical depictions of the results can assist in identifying threshold phenomena and other non-linear relationships that may be inherent to the fish-factor interaction. In utilizing the affinity analysis approach, care must be taken to consider collinearity between variables, as well as appropriate segmentation of the attribute range in depictions of continuous data.

The environmental attributes that appeared to be both pertinent and met data-adequacy criteria for inclusion in the affinity analysis (from Table 1) were turbidity, salinity, temperature, food availability, channel depth, channel width, water body type, area of shallow water, proximity to wetlands, and substrate during spawning.

In conducting the affinity analyses, we divided the full range of data for each attribute into 6 to 9 segments (or increments). The delineation of the segments reflected the nature of the attribute considered. The segments were generally of equal magnitude through the range of interest for turbidity and depth. For temperature, the magnitudes of some segments were narrowed for some segments to provide more detailed information for the response variable (for example, temperatures during summer that might induce stress). For other attributes, including salinity, turbidity, prey density, channel depth, area of shallows, and distance to wetlands, the delineation of segments reflected a near exponential spacing. Other delineations reflected discrete categories of the attribute (for water body type and substrate).

For each monitoring-program month during which a targeted life stage was abundant (that defined here as exceeding 10% of the annual total of individuals sampled), we used pivot tables (in Microsoft Excel) to enumerate the number of delta smelt individuals and the number of observations in each attribute segment. We then converted each of those to a percentage value for each month, and generated summary statistics across months and years to produce statistics on the average percentage of availability for each attribute segment, the average use of each segment, the average difference between the two, and the standard deviations of each to determine a 90% confidence interval.

We present affinity analyses as graphs for each life stage showing the percentage distribution of delta smelt across a segmented attribute range compared to the availability of the resource. We display the difference between resource availability and its use, along with the 90% confidence interval surrounding the difference.

Derivation of Suitability Indexes

It has been usual practice to present the value of an environmental attribute to a species in a habitat suitability index, as demonstrated by its application to more than 50 fish species (http://el.erdc.usace.army.mil/emrrp/emris/emrishelp3/list_of_habitat_suitability_index_hsi_models_pac.htm). Suitability indexes are hypothetical models, which are typically developed from a review and synthesis of existing information on the established use of a resource by that species. The relationship is scaled to produce an index of habitat suitability on a scale between 0 (unsuitable habitat) and 1 (optimally suitable habitat) (see Weinstein 1986). Guay et al. (2000) utilized affinity studies to develop suitability indexes for juvenile Atlantic salmon, which they referred to as "preference indexes." We largely follow that approach by employing average use-to-availability ratios across months and years for each attribute segment and life stage to assess factor suitability for delta smelt. But Guay and his colleagues utilized the maximum score from the use-to-availability ratio to scale remaining ratios in other segments, while we used either that ratio or 1, whichever was less, in an attempt to differentiate suitable environmental attribute ranges (that is, those with a suitability index values equaling 1) from ranges less suitable. In so doing, we recognize that expressed preference or aversion by a species to a specific environmental factor and condition is relative – individuals may actually inhabit a location because conditions there are "better" than at alternative locations, not necessarily because the location offers environmental conditions that might be described as optimal, good, or even adequate. Rather than producing peaked functions similar to those presented by Guay et al., our approach produces an attenuated (flatter) response, more representative of the response functions that might be inferred from historical distributions of fish and environmental conditions in the Delta (Pardue 1983, Weinstein 1986, Stier and Crance 1985). To obtain values for the entire range of an attribute with continuous values, we used linear interpolation between the index values at the midpoints of each segment.

Development of numerical indexes for habitat quality

An indication of the overall suitability of prevailing environmental conditions for delta smelt at any geographic location (l) and any point in time (t) may be derived by calculating a Habitat Suitability Index (HSI), the geometric mean of suitability indexes for multiple individual attributes (S_i) (Brown et al 2000, Guay et al 2000), with:

$HS_{lt} = \Pi S_{ilt}$

HSI values can then be aggregated over space and time to enumerate the quality of habit in a region or over time.

We expanded on this approach by calculating a weighted geometric mean, offered as:

$HSI_{lt} = \alpha \Pi S_{ilt}^{\beta i}$

We calculated the weights, β_i, by regressing the suitability values in log form against the log of the percentage of delta smelt at a given survey station. A value of 0.01 was added to time series that included zero values to allow the logarithmic calculation. We chose to use the relative distribution of delta smelt, rather than absolute densities, to correct for inter-annual variation in abundances. We use the results of the multiple regression analysis both to identify significant attributes and to calculate a weighted HSI for each observation.

Spatial Depictions

Having identified environmental variables that appear to influence the distribution of delta smelt, the final element of the study was to identify how frequently environmental attributes occur in ranges that may be less than adequate, and where these circumstances occur, to suggest an appropriate type of restoration activity and location for a next level of management planning consideration.

We calculated the frequency with which attributes were less than adequate (that is, exhibited suitability index values in an aversion range) for turbidity, salinity, temperature, and prey density. We also identified locations where water depth was considered less than adequate (using estuary-wide bathymetric data) or where wetlands could be considered too distant. This enabled us to identify areas for potential channel modification and wetlands restoration. We developed criteria for candidate restoration sites where elevations approximate sea level (to utilize tidal processes without undue earthwork) or areas where other environmental attributes frequently occur in adequate ranges (to increase the likelihood of use by the species). We did not attempt to evaluate any potential sites in Suisun Marsh, because we do not have the detailed understanding of the hydraulic connectivity between tidal marshlands and main channels that is needed for such an evaluation.

On terminology

Acknowledging that the de rigueur terms used to convey "preferences" by organisms for essential resources, other environmental attributes, and landscape circumstances tend to default to value judgments -- we see that environmental conditions are sometimes described as "optimal," or as near anthropomorphisms, wherein conditions are often referred to as "desirable" -- we have restricted this presentation to a purposefully neutral terminology. We describe delta smelt as showing *strong affinity* or *strong aversion* for environmental attribute conditions where survey returns indicate that the difference between delta smelt occurrences in a range segment and availability of that range segment in the estuary is significantly different from zero at the 90% level of confidence. Environmental conditions in areas to which delta smelt show strong affinity are considered *suitable;* conditions where delta smelt exhibit a strong aversion are *inadequate.* Where delta smelt exhibit weak affinity, areas are referred to as *adequate.*

RESULTS

Affinity Analyses

Delta smelt associations with seven environmental attributes of (or resources in) the estuary for five life stages during six sampling periods are presented as histograms in Figures 2-8. These seven attributes can be inferred to contribute to delta smelt habitat – turbidity, salinity, temperature, food availability, sub-surface depth, extent of shallow water, and distance to large wetlands. Affinity studies for water body type, water body width, and substrate at spawning revealed no notable relationships that appear to inform habitat restoration. Delta smelt life stages are described as expressing affinity for a range of conditions for each environmental attribute, where the attribute or resource use or co-occurrence (the height of the red column) exceeds that of relative attribute or resource availability (the height of the blue column with which it is paired). Delta smelt are averse to conditions that exhibit that relationship in reverse. Differences between the paired columns are depicted with green dots bracketed by a 90% confidence interval and referenced by the right axis. Results are summarized in Table 4. Life stage-specific affinities and aversions for the suite of environmental attribute conditions can be summed to shape a multi-dimensional description of delta smelt habitat, which can be used to inform habitat restoration efforts targeting delta smelt. A "habitat space" emerges from pairing distribution data for each delta smelt life stage, with temporally appropriate data on each environmental attribute.

Sub-juvenile delta smelt are sampled while dispersing from shallow spawning areas to open water areas in which they then feed and grow. Having less-developed swimming abilities, they do not express associations with environmental attributes as closely as they appear to in later life stages. Sub-juveniles do express a strong affinity for moderate turbidity (20-40 cm) (Figure 2a). And, while sub-juveniles are frequently found in near-freshwater conditions typical of spawning areas (Figure 3a), they are tolerant of salinities up to 4000 Ec. Water temperatures are rarely in the ranges that might induce stress in this life stage, but sub-juveniles seem to avoid waters in excess of 22 degrees C (Figure 4a). No consistent pattern of sub-juvenile distribution emerges across the range of bathymetric characteristics in the estuary, although strong affinity exists for water deeper than 7m (Figure 6a), and at least a limited area (5-20 ha) of shallow-water circumstances (Figure 7a). A requirement for channel complexity – essentially deep channels that meander through tidal marshlands – is consistent with conditions that were present in the pre-settlement estuary. No strong affinity is expressed by sub-juveniles for prey density (Figure 5a), perhaps reflecting two factors -- sub-juveniles are a life stage in transit,

Table 4. *Affinity ranges for delta smelt for seven environmental attributes in the estuary. This table is a summary of the affinity analyses presented in Appendix A. A "suitable" range depicts conditions where delta smelt demonstrated relative use of an attribute range that is significantly greater than the relative availability of that range. A "weak affinity" range depicts attribute ranges where relative use exceeds relative availability. An "inadequate" range depicts conditions where relative use is significantly less than relative availability.*

	Affinity	**Spring**	**Spring**	**Summer**	**Fall**	**Winter**	**Winter**
Life-stage		Sub-juvenile	Juveniles	Juveniles	Sub-Adults	Pre-spawning Adults	Spawning Adults
Primary Months		May-Jun	Jun-Jul	Jun-Aug	Sep-Dec	Jan-Feb	Mar-Apr
Program		20mm	20mm	STN	FMWT	Kodiak	Kodiak
Turbidity	Suitable	20-40	20-40	20-40	30-60	20-30	20-30
(Secchi	Weak affinity	10-50	10-40	0-50	0-60	0-40	20-50
depth cm)	Inadequate	>50	>50	>50	60-70,>80	>60	50-60,>70
Salinity	Suitable	200-1000	1000-4000	1000-4000	1000-8000	1000-4000	-
(Ec)	Weak affinity	200-4000	200-8000	1000-8000	200-12000	1000-8000	200-600 1000-8000
	Inadequate	>4000	<200, >16000	<400, >16000	<200, >20000	<200, >8000	<200, >8000
Temper-	Suitable	20-21	20-21	18-22	-	-	-
ature	Weak affinity	18-22	18-21	18-22	16-21	13-15	12-15
(Celcius)	Inadequate	12-18,>22	16-18,>22	>22	-	-	-
Calenoid	Suitable	1000-2500	250-2500	-	>1000	250-1000	-
Copepods	Weak affinity	-	100-2500	1000-2500	>250	100-2500	250-1000
(#/m^3)	Inadequate	-	<1,>2500	<10	-	-	10-100
Depth	Suitable	>7	7-9	<3, 7-9	7-9	5-6	5-6
(meters)	Weak affinity	various	<3	<3,7-9	6-12	4-6	5-6,>9
	Inadequate	2-4	4-7	4-7	<5	<4,6-7	<4,6-7
Area of	Suitable	5-20	>100	>100	5-20	5-20	-
Shallows	Weak affinity	5-20, >200	>100	5-20,>100	5-20	5-20,>200	5-20,>200
(ha)	Inadequate	20-50	<5	<5,20-100	<5,>20	20-100	50-100
Distance	Suitable	1-2, 3-5	1-2, 3-5	1-2, 3-5	0.5-2	0-0.25	-
from Wetlands	Weak affinity	1-2, 3-5	0.25-0.5, 1-2, 3-5	0.25-0.5, 1-2, 3-5	0-2	0-0.25,1-2	< 0-0.25, 1-2
km	Inadequate	>5	>5	>5	>3	>5	>5

and there may be a complex interaction between prey and predators that affects copepod densities, which is poorly accounted for in the available data. While a strong affinity by delta smelt for areas supporting greater prey density is not demonstrated, there is an affinity for areas in (close) proximity to wetlands (Figure 8a), which becomes more evident in later life stages.

For *juvenile delta smelt*, a strong affinity exists for turbid water less than 40cm Secchi depth (Figure 2b and 2c). Juveniles demonstrate an affinity for waters with salinity up to 8000 Ec (Figures 3b and 3c). They exhibit a strong aversion to water greater than 22 degrees C and are rarely found in circumstances exceeding 23 degrees C (Figures 4b and 4c). An affinity for water depth more than 7 m (Figure 6b and 6c) and for adjacent shallow areas exceeding 100 ha in extent is apparent (Figures 7b and 7c). The primary area where this suitable condition occurs is in Grizzly Bay; a large area of shallow water into which (presumably) nutrient-rich water from Montezuma Slough empties, providing a food source to a life stage with a not yet fully developed swimming capacity. An affinity for prey densities exceeding 250 individual copepods per m^3 is pronounced in juvenile delta smelt (Figure 5b), as is an affinity for areas within 2 km of wetlands (Figure 8b and 8c). Juveniles appear to express a strong aversion for locations that support high prey densities -- likely an anomaly reflecting the presence of higher prey densities in the south Delta at times when prevailing turbidity or temperature conditions there limit occupancy by delta smelt.

Sub-adult delta smelt appear to be tolerant of a wider range of environmental conditions than earlier stages, likely due to the need for that life stage to cope with variability in several environmental attributes in autumn in the estuary. For example, sub-adults are more tolerant of clear water (Figure 2) and fresh water (Figure 3). They exhibit a weak affinity for salinities up to 8000 Ec, not expressing strong aversion until salinity exceeds 20000 Ec (Figure 3d), twice the salinity level at which aversion is shown by juveniles. Few sub-adults are found in water exceeding 23 degrees C (Figure 4d). Sub-adults show a strong affinity for water 7-9 m in depth (Figure 6d) and for situations where limited shallow water areas (5-20 ha) exist nearby (Figure 7d), reflecting a continuing association with complex bathymetry. A strong affinity for prey density is not exhibited by sub-adult delta smelt until copepod density exceeds 1000 per m^3 (Figure 5d), perhaps reflecting increased food requirements at this life stage. Sub-adults are found close to larger wetland areas, with strong affinities expressed for locations less than 2km from them (Figure 8d).

The *pre-spawning adult delta smelt* that are found predominately in survey samples taken in January and February, are presumably taken while dispersing to spawning areas. While they exhibit affinities and aversions, few are as strong as displayed by other life stages. An affinity for turbidity is exhibited in the 20-30 cm Secchi-depth range segment (Figure 2e). The affinity range for salinity is 1000 to 8000 Ec (Figure 3e), with an aversion to freshwater (that is, less than 200 Ec). There appears to be no influence of water temperature on the distribution of pre-spawning adults (Figure 4e). Affinity exists for situations adjacent to limited shallow water circumstances (5-20 ha) (Figure 7e). An affinity for depth conditions appears shift to waters 5 to 6 m deep (Figure 6e), perhaps reflecting dispersal to spawning areas in shallower situations. Pre-spawning adults express an affinity for locations with densities of copepods in the range of 250 to 1000 /m^3, which is an affinity range lower than observed in previous life stages but locations with copepods at 1000/m^3 are rare at this time of the year (hence pre-spawning adults exhibit an affinity for the highest prey densities available). An affinity for locations in proximity to wetlands is strong; highest with wetlands in the range of less than 250 meters distant (Figure 8e), suggesting that wetlands may not only be important for food production, but that they also provide some essential conditions for reproduction.

Spawning adults sampled in trawl surveys number the fewest of all life stages. Since the reduction in abundance from pre-spawning to spawning adults is far greater than would be expected due to natural attrition, it is likely that the spawning adults are moving away from the monitoring sites. The few spawners sampled and the truncated duration of the Spring Kodiak Trawl makes it difficult to identify the range of suitable environmental attributes, and, as with other fishes, it might be assumed that spawning areas exhibit attribute conditions that are suitable for the eggs and larvae to come. Spawning adults do express strong affinity for turbid water (20-30 cm Secchi depth), and avoid clear water (greater than 50 cm Secchi depth) (Figure 2f). Interestingly, spawning adults exhibit an aversion to very fresh water (Ec less than 200) (Figure 3f) despite the common description of spawning adults as moving to fresh water to spawn. As with pre-spawning adults, temperature seems to play no apparent role in the distribution of fish at this life stage (Figure 4f); likewise the area of shallow water seems to have no bearing on distribution (Figure 7f), although there is an association with water 5 to 6 meters deep (Figure 6f). Spawning adults avoid areas with little food ($<100/m^3$) (Figure 5f), and express an affinity for waters within 0.25 km and 1 to 2 km of large wetlands (Figure 8f).

Habitat Suitability

Given the purpose of this study -- to identify areas that should benefit from restoration efforts targeting delta smelt and to identify particular management actions at specific sites -- we focus on the areas where physical and biotic conditions are frequently unsuitable, allowing planners to exclude those areas, and in so doing, identify residual areas that may be suitable for physical and biological restoration actions.

Maps illustrating the distribution of categorical environmental variable conditions – turbidity, salinity, temperature, prey density, water depth, extent of shallow water, and distance to large wetlands (Figures 9 to 16 and Appendix A) illustrate in a spatially explicit format the extent to which sub-areas of the estuary are inadequate or unsuitable for delta smelt (see Table 4).

During June and July, the water in the south Delta is frequently too clear (not sufficiently turbid) to provide suitable conditions for delta smelt (Figure 9). At the same time conditions in the area from Liberty Island west to the Lower Napa River are rarely unsuitable. In the fall, areas of the estuary with turbidity in a suitable range are greatly reduced (Figure A-1, in Appendix), with suitable turbidities limited to the northern portion of Suisun Bay, Montezuma Slough, areas around the Sacramento-San Joaquin rivers confluence, and the Sacramento ship channel.

Portions of the estuary can be too fresh in places (Figures 10, A-2) and too saline in other places (Figures 11 and A-3) to be suitable for delta smelt. Between these limits in the west and east extremes of the estuary, delta smelt persist in diverse circumstances. Suisun Bay and Montezuma Slough rarely experience water conditions that are too fresh in June and July, whereas the lower Sacramento River and lower San Joaquin River, upstream of the confluence with Old River, frequently experience water that is too fresh for delta smelt (Figure A-2). In the fall, only the north delta above Rio Vista and the east Delta offer water conditions that may be too fresh for delta smelt (Figure 10).

In June and July, water conditions in the far western portion of Suisun Bay can be too saline, hence not suitable for delta smelt (Figure A-3). Salinity levels increase in the fall, but the tolerance of delta smelt to salinity also increases. The net effect is that a generally similar area of western Suisun Bay may be too saline to be suitable for delta smelt (Figure 11).

Locations where water temperatures exceed 22 degrees C are avoided by delta smelt. Such temperatures are common in the south and east Delta during June and July (Figure 12).

Prey density does not correlate well with the existing distribution of delta smelt. Densities in June and July are highest in the south Delta (Figure A-4), although these areas frequently have other attributes in ranges that are unsuitable for delta smelt. But pockets with higher prey densities exist in the central portion of the range. In the fall, the data suggest that the estuary widely exhibits limitations on food availability (Figure A-5).

Delta smelt express strong affinities for waters of certain depths. Channels in north Suisun Bay and Montezuma Slough, although including sites with high densities of delta smelt, include extensive channels with insufficient depth (Figure 14).

The affinity results for areas of shallow water suggest that, for most delta smelt life stages, at least limited areas of shallow water are an important element of habitat. While the availability of such circumstances is frequent in the estuary (Figure A-6), some areas could benefit from targeted rehabilitation for the attribute. Such projects may be readily and efficiently combined with wetland restoration projects – projects that require such significant landscape modification. Wetlands are often identified as an important contributor to the lower levels of the food web. While large wetlands are prevalent throughout Suisun Bay and adjoining waters, they are sparse throughout most of the rest of the estuary (Figure 14).

Significance of environmental attributes

The maps that depict the frequency with which individual physical and biotic attributes are inadequate (Figures 9 to 14) indicate that the estuary is both spatially and temporally complex and variable. In an effort to determine those environmental attributes that may be relevant in restoration planning – versus those that may essentially be redundant – in a multivariate context, we first derived suitability index curves (presented in Appendix B) from the results of the affinity analyses (Figures 2 to 8). Next, we regressed the suitability index values for the seven habitat attributes against the relative distribution of delta smelt.

When prey density is excluded from the analysis, the results indicate that turbidity, salinity, and average water depth influence the distribution of delta smelt at all life stages (Table 5). Temperature is a significant determinant of distribution for sub-juvenile and juvenile life stages. Distance to wetlands is significant at juvenile and sub-adult life stages. The area of shallow-water circumstances is significant for juveniles in mid summer (based on Summer Tow-net survey data) and for pre-spawning and spawning adults.

Table 5. *Results of multiple regression analysis when distribution of delta smelt (dependent variable) is regressed against the habitat suitability index values of six habitat attributes during various life stages; "negative" indicates the regression coefficient had a negative sign.*

Attribute	Sub-juvenile		Juvenile (20mm)		Juvenile (STN)		Sub-adult		Pre-spawning adult		Spawning adult	
n	2592		2016		2809		9246		686		614	
	Coeff	P-value	Coeff	P-value	Coeff	P-value	Coeff	P-value	Coeff	P-value	Coeff	P-value
Turbidity	0.31	<0.001	0.09	<0.001	0.05	<0.001	0.21	<0.001	0.26	<0.001	0.19	0.001
Salinity	0.17	<0.001	0.22	<0.001	0.47	<0.001	0.37	<0.001	0.81	<0.001	0.29	0.011
Temperature	0.23	<0.001	0.14	<0.001	0.05	0.031	Negative		Negative		0.12	0.774
Depth	0.44	<0.001	0.19	<0.001	0.40	<0.001	0.33	<0.001	0.15	0.041	0.12	0.024
Shallows Area	Negative		Negative		0.18	<0.001	Negative		0.54	<0.001	0.27	0.021
Wetlands Distance	0.02	0.460	0.16	<0.001	0.22	<0.001	0.36	<0.001	0.10	0.139	Negative	

When copepod prey density is included in the analysis (Table 6), prey density is significant only for the juvenile life stage during June and July (based on 20mm data), and the pre-spawning life stage. The coefficient for prey density has a negative sign for sub-juveniles

Table 6. *Results of multiple regression analysis when distribution of delta smelt (dependent variable) is regressed against the habitat suitability index values of seven habitat attributes during various life stages; "negative" indicates that the regression coefficient had a negative sign.*

Attribute	Sub-juvenile		Juvenile (20mm)		Juvenile (STN)		Sub-adult		Pre-spawning adult		Spawning adult	
n	2378		1835		2750		5792		424		376	
	Coeff	P-value	Coeff	P-value	Coeff	P-value	Coeff	P-value	Coeff	P-value	Coeff	P-value
Turbidity	0.30	<0.001	0.10	<0.001	0.05	<0.001	0.27	<0.001	0.28	<0.001	0.18	0.012
Salinity	0.19	<0.001	0.20	<0.001	0.44	<0.001	0.40	<0.001	0.53	0.014	0.27	0.141
Temperature	0.25	<0.001	0.15	<0.001	0.06	0.016	0.04	<0.001	0.06	0.694	0.33	0.525
Depth	0.53	<0.001	0.20	<0.001	0.39	<0.001	0.43	<0.001	0.19	0.067	0.11	0.156
Shallows Area	Negative		Negative		0.16	<0.001	Negative		0.82	<0.001	0.21	0.162
Wetlands Distance	0.12	0.009	0.17	<0.001	0.23	<0.001	0.14	<0.001	Negative		Negative	
Prey Density	Negative		0.26	<0.001	0.02	0.061	Negative		0.89	0.002	0.09	0.145

and sub-adults, possibly due to collinearity with other variables. Turbidity is significant at all life stages. Salinity is significant at all but the spawning life stage. Average depth, temperature, and distance to larger wetlands (> 100 ha) are significant for sub-juvenile, juvenile and sub-adult life stages. Area of shallows is significant for juveniles in mid summer (based on Summer Tow-net Survey data) and for pre-spawning adults.
To identify landscape areas that are most likely to host successful restoration programs, we summarized the abiotic (water quality) attributes (turbidity, salinity and temperature) into

an average HSI for each station. The HSI was derived from a weighted geometric mean of the suitability index values for the attributes, utilizing the coefficients from Table 5 as the weights. We depicted the average value for each station geographically both for juveniles in the 20 mm Survey and pre-spawning adults in the Spring Kodiak trawl (see Figure 15). This figure indicates that areas in the vicinity of Suisun Marsh, at the confluence of the Sacramento and San Joaquin rivers and in the north Delta have the highest geometrically weighted average HSI values for abiotic (water quality) attributes, and can be viewed as representing potential priority target areas for habitat restoration efforts.

Restoration Guidance

The results presented in Tables 5 and 6 indicate that modification of channel depth or restoration of emergent wetlands (tidal marsh, freshwater marsh, and riparian strands) could substantively improve the overall suitability of environmental conditions for delta smelt at locations where other environmental attributes are frequently in suitable ranges. The geographic distribution of areas that are most likely to benefit delta smelt from environmental restoration (habitat improvement) efforts is provided in Figure 15. We suggest that these types of maps (at finer resolution) can assist in establishing priorities for early-term projects where habitat suitability for delta smelt can be enhanced through improvement focused on a select environmental attribute. Examples of potential project sites in priority target areas are presented in Figure 16 (for channel modification and wetlands restoration).

DISCUSSION

Survey returns for multiple life stages of delta smelt were analyzed with time-series data drawn from a collection of environmental factors in an effort to provide guidance to a habitat conservation planning process. The affinity analyses appear to offer contingent explanations for patterns of presence and absence by the fish, and support the observation that delta smelt demonstrate an ability to seek out habitat and maintain presence in suitable locations. Delta smelt habitat requirements, or more exactly the physical and biotic conditions required for delta smelt presence, are multi-dimensional and for some attributes vary with life stage. Maps of the distribution of delta smelt in the estuary offer insights into delta smelt habitat requirements on two spatial scales salient to planning for restoration of habitat for the species. Broad patterns of spatial variation in water-quality factors indicate that large portions of the estuary are frequently unsuitable for delta smelt. Within areas that are more frequently suitable, site-specific differences in water-body and channel morphology, and proximity to emergent wetlands, offer a mechanistic explanation for patterns of delta smelt distribution on the location level, that is, on scale of a kilometer, more or less.

An operational description of habitat can be drawn from this study and set in the context of previous work that includes laboratory studies and other assessments of longer-term data sets from the estuary (see particularly Bennett 2005 for a synthesis). Such a descriptor can provide a basis for identifying sites suitable for habitat restoration for delta smelt, setting life stage-specific objectives for management actions, and assessing program performance in an indicator-based monitoring and assessment scheme.

> "Habitat for delta smelt includes areas in the northern and central estuary that are characterized by complex bathymetry, with deep channels close to shallows and shorelines, with little submerged vegetation, but immediately bounded by extensive tidal or freshwater marshlands. Such situations appear to contribute to local production of diatom-rich phytoplankton communities that support calanoid copepods, in particular *Eurytemora* and *Pseudodioptomus*, and some cyclopoid zooplankton, which are frequent in the diets of delta smelt. The fish demonstrates affinities for waters that experience salinity in the range of 200-8000 EC, a water transparency less than 50 cm, and temperatures below 22 degrees Celsius, with preferred conditions varying somewhat with life stage. Before spawning, delta smelt initiate a diffuse landward dispersal to fresher-water circumstances, and while little is known about the microhabitat conditions required for successful spawning, preferred substrates may include clean cobble or sandy surfaces to which eggs are adhered. Delta smelt frequently are found in open water situations, but less so during spawning. Where pre-spawning delta smelt must disperse greater distances to spawning areas, intervening areas of the estuary, including some areas with conditions less suitable for delta smelt, are included as habitat."

The full array of physical and biotic attributes necessary to consistently support delta smelt, set in spatial context with necessary adjacency and adequate temporal availability, is found in relatively limited areas of the contemporary estuary – an observation that suggests that the restoration challenge to be met for delta smelt is great and the opportunities not so many. Importantly, the findings presented here can guide a parsimonious approach to habitat restoration for delta smelt. The creation of habitat, or the restoration of areas that exhibit attributes within affinity ranges for delta smelt (but are currently unsuitable) inside the contemporary range of the fish, might be expected to enhance its productivity and its likelihood of persistence. An interpretation of the affinity analyses presented here can inform prioritization of potential restoration efforts. All restoration projects require direct engagement of resources, and frequently redirection of resources away from other beneficial applications, which inevitably has both ecological and economic consequences. We have attempted to identify and locate candidate project actions with such consequences in mind, preferring as highest-priority projects those that fall within the existing geographic range of delta smelt, require minimal redirection of other resources, and can be implemented where the geographic extent of actions needed is limited – in other words, where more focused restoration efforts targeting fewer environmental attributes (habitat factors) are addressed on landscape areas adjacent to locations that already support delta smelt.

That recommendation married with spatially explicit observations from the affinity analyses and mapped data can form the foundation for a strategic approach to restoration site selection and site-specific management planning. A number of findings from the affinity analysis can kick-start such a process.

From analyses using trawl survey data, delta smelt demonstrate an affinity for certain environmental conditions that differ significantly from the frequency with which those conditions occur in the estuary. And, delta smelt occupy a continuum of suitable areas of the estuary, and avoid areas of the estuary with environmental attributes in less than adequate ranges. The affinity analyses indicate that different portions of the Delta exhibit diverse conditions for seven environmental variables that contribute to habitat extent and quality for delta smelt. Different sub-regions of the estuary and local areas within those sub-regions vary in their suitability for delta smelt, and do so in discordant patterns. The results of analyses in this study facilitate identification of areas of the Delta that offer environmental conditions in acceptable and unacceptable ranges.

Three factors related to water quality -- turbidity, salinity, and temperature -- while not competent to describe the habitat space available to delta smelt, contribute to defining the space available for habitat restoration actions targeting delta smelt. Certain areas of the estuary exhibit water-quality attributes and conditions that cannot readily be addressed through targeted management actions in the estuary (for example, reduced turbidity in the San Joaquin River and southeastern Delta, which in part may be resulting from sediment impoundments behind tributary dams that are located far from the conservation planning area), or may be effected by attribute trajectories that suggest that future conditions may render additional portions of the estuary unsuitable for delta smelt (for example, water temperatures in the estuary that can be anticipated to rise). So, at different spatial scales, many areas of the estuary appear to be unsuitable, with multiple environmental attributes falling outside of a range that is suitable to support delta smelt; but other areas appear to be unsuitable because just one factor (among those investigated here) falls outside that range. Habitat restoration prescriptions should acknowledge that southern and eastern portions of the estuary are frequently too clear in the fall and too warm in the summer to provide effective year-round habitat for delta smelt. In contrast, a wide swath of the estuary, from Suisun Bay and Suisun Marsh in the west to Cache Slough and the Sacramento ship channel in the east, largely experiences turbidity and temperature conditions suitable for delta smelt. In the fall, the range of delta smelt in the estuary is located between water that is too saline in the west (west of Suisun Bay) and too fresh in the east (in the upper Sacramento River near and north of Rio Vista).

Delta smelt habitat requirements, or more exactly the physical and biotic conditions required for delta smelt presence, are multi-dimensional. The findings presented here indicate that habitat restoration efforts for delta smelt must consider, on the one hand, the broad ranges in, and geographic patterns exhibited by, water turbidity, salinity and temperature conditions, which vary by life stage; and, on the other hand, the availability of adequate supplies of copepod prey, and heterogeneous bathymetry where deep channels are found in proximity to shallower circumstances and emergent wetlands. The mapped analyses presented illustrate potential trade-offs that may be important in restoration planning decisions. For example, water management decisions that contribute to shifting the location of the low-salinity zone in the Delta to the west (downstream, as proscribed under certain “water-year” circumstances in a recent delta smelt biological opinion [USFWS 2008]) may improve habitat conditions in some parts of the estuary, but will at the same time render other areas less suitable or unsuitable to delta smelt during portions of the year.

We have attempted to identify the habitat requirements of delta smelt and locate candidate project actions and locations, preferring as highest-priority projects those that fall within the existing geographic range of delta smelt, and require minimal redirection of other resources. The copepod prey that supports delta smelt frequently appears to be limiting in early summer in the northern portions of the estuary and in Napa River and its estuary -- along with that situation, widely distributed food shortages occur across the estuary in the fall. It is likely that tidal marsh and freshwater marsh restoration (and creation) in northern portions of the estuary would serve to enhance the availability of food-producing and spawning areas. More specifically, we conclude that restoration of large emergent wetlands in eastern Montezuma Slough, the Sacramento River below Isleton, and in the Cache Slough area could improve habitat availability for delta smelt. Furthermore, it appears that habitat conditions in areas in north Suisun Bay and Montezuma Slough could be improved with channel modifications, and increasing the availability of areas of shallow water in Grizzly Bay, Suisun Bay, and some stretches of the Sacramento River could improve habitat in those areas for young delta smelt.

The results of the affinity analyses have immediate application. The proposal to restore habitat for delta smelt in the BDCP is embedded in a conservation strategy that follows a controversial biological opinion produced by the U.S. Fish and Wildlife Service in 2008, which determined that ongoing water export operations from the estuary by state and federal pumping projects jeopardizes the continued existence of the delta smelt. While recognizing that a broad array of physical and biotic factors provide essential resources and contribute to habitat for delta smelt, the Service chose to use the location of the low-salinity zone in the estuary as a surrogate measure of the extent and quality of habitat for delta smelt. The BDCP is following the agency lead by employing the location of the low-salinity zone, which expands during periods of high outflow through the estuary, as proxy for the summed environmental attributes that must co-occur to allow for the presence delta smelt. The plan infers that increased suitable habitat for delta smelt becomes available when the low-salinity zone is particularly expansive, and it measures benefits to delta smelt and program success as a function of a salinity-habitat relationship. None of these assertions is supported by the affinity analyses. The present study does confirm that the salinity gradient is a substantive deterministic factor that contributes to the suitability of the estuary for delta smelt. But, salinity is a "coarse filter" (see Noon, et al. 2007) for purposes of conservation planning for delta smelt; providing little guidance to site-specific restoration efforts beyond setting wide bounds on the estuary landscape within which directed management actions should occur. As the maps accompanying the affinity analyses clearly indicate, the location of the low-salinity zone is a weak predictor of the presence of delta smelt at the scale that habitat restoration for the species will be carried out. Salinity thus cannot be viewed as an effective surrogate for, or environmental indicator of, habitat for delta smelt.

The validity of our conclusions here are, of course, related to the reliability of the survey data on delta smelt and the accompanying environmental variables upon which the affinity analysis was based. The longer time-series data sets on delta smelt that were used in this study are derived from trawler-based surveys of fishes in the estuary's open waters; few samples in shorter time-series are drawn across bathymetric gradients. The water quality variable data were taken concurrently, hence are similarly limited. Zooplankton data are largely collected independently, and suffer from degrees of spatial and temporal discordance with delta smelt samples. Both the fish survey and environmental factor data sets are derived from studies that very unfortunately are limited in geographic footprint, missing data from essential geographic locations on the estuary's periphery, where range limits of environmental attributes are commonplace. These shortcomings in the database for the estuary will need to be rectified in any performance measure-based monitoring efforts that are developed to accompany restoration efforts. But, given the ambitions of this study and its accompanying information needs, the extent and resolution of the data might fairly be viewed as adequate. At the same time, the urgency for restoration actions within the estuary to facilitate the recovery of protected native fishes cannot wait for improved monitoring programs -- restoration must proceed utilizing the best currently available data.

The absence of well-resolved environmental variables, beyond the seven used in the habitat affinity analyses carried out here, has implications to restoration planning. Geographic patterns of predation on delta smelt and contaminant loading are lead concerns in the conservation of the species. Concerning the latter, one contaminant that has been recorded in ecologically relevant concentrations in areas occupied by and adjacent to delta smelt, ammonium, which is released from municipal wastewater treatment facilities, creates imbalances in nitrogen-phosphorus ratios and contributes to increases in chemically reduced nitrogen concentrations that impair primary productivity (Dugdale et al 2007) and are correlated with food web disruption, including reduced availability of diatom species that serve as prey for the zooplankton upon which delta smelt depend (Glibert et al 2011). Changes in nutrient ratios and nutrient concentrations, which are associated with elevated ammonium, create conditions conducive to invasions of rooted aquatic vegetation, toxic blue-green algae, and bi-valve mollusks (Glibert et al 2011), all habitat quality-compromising stressors that are thought to have direct and indirect deleterious effects on delta smelt abundance. Otherwise well-crafted restoration efforts in locations that could be expected to support delta smelt, could well fail or under perform due to local stressor conditions that could not be considered in this study.

The approach to assessing estuary conditions for delta smelt taken here uses environmental variables on water quality, food availability, morphological water-body and channel characteristics, and proximity to wetlands to describe the multidimensional space that supports much of the current distribution of multiple delta smelt life stages. Using a diversity of estuary attributes in the affinity analysis (in contrast to a narrow array of water quality variables -- see USFWS 2008) -- allows for a (more) comprehensive characterization of conditions that are acceptable, and conversely appear to be undesirable, to delta smelt. The environmental variables considered here shed light on resource conditions that appear to determine the presence and absence of delta smelt at a range of spatial scales. Guidance that can be gleaned from this study for future environmental restoration efforts targeting delta smelt includes, not just identification of areas of the estuary that should be avoided because they are unlikely to support delta smelt regardless of restoration actions, but also direction toward areas where actions are likely to succeed in enhancing delta smelt productivity, and identification of the restoration and enhancement measures necessary to generate and sustain that productivity. All restoration projects require direct engagement of resources, frequently redirection of resources away from other beneficial applications, which inevitably has both ecological and economic consequences. We believe it would not be prudent to invest in management or restoration actions for delta smelt in areas that are projected to be deleteriously impacted by water quality variables that fall out of the range of suitability for delta smelt.

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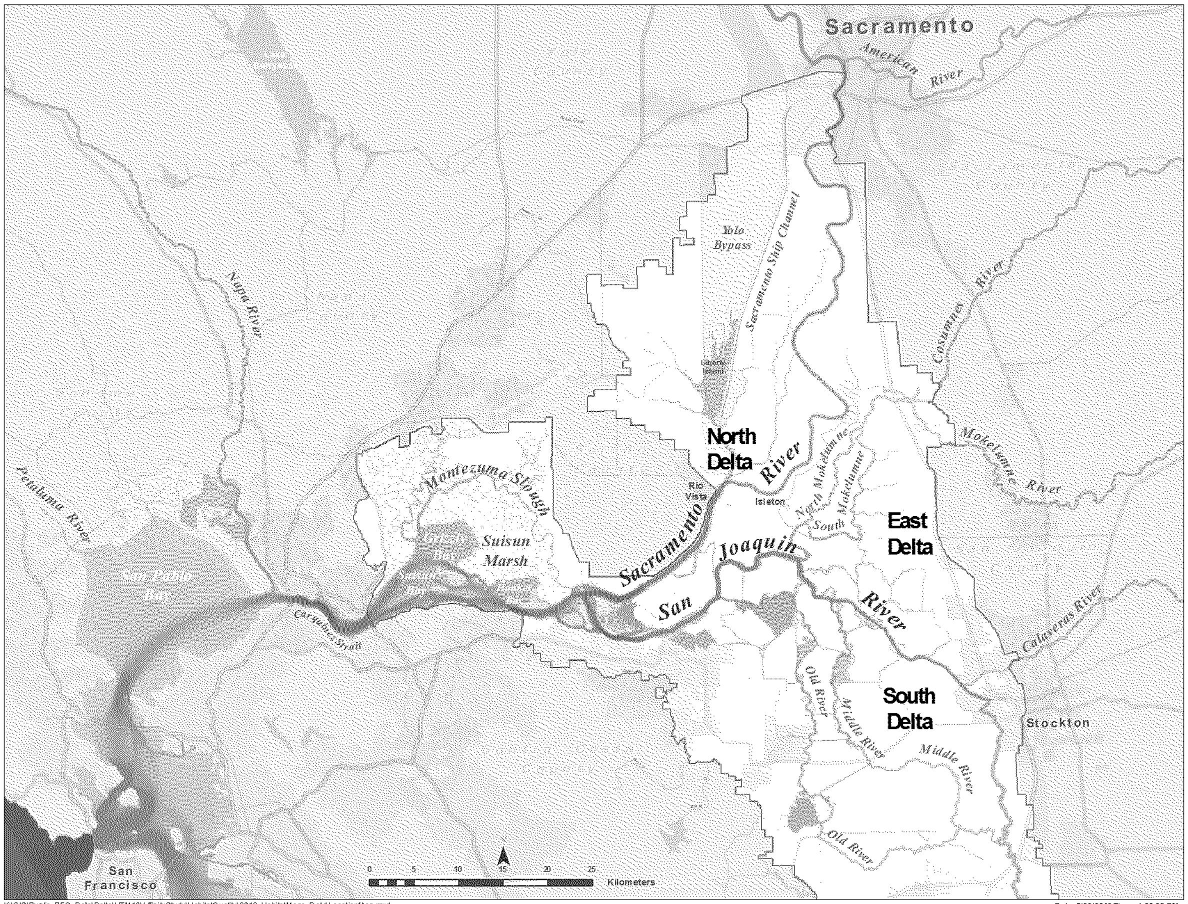

Figure 1. The San Francisco Estuary.

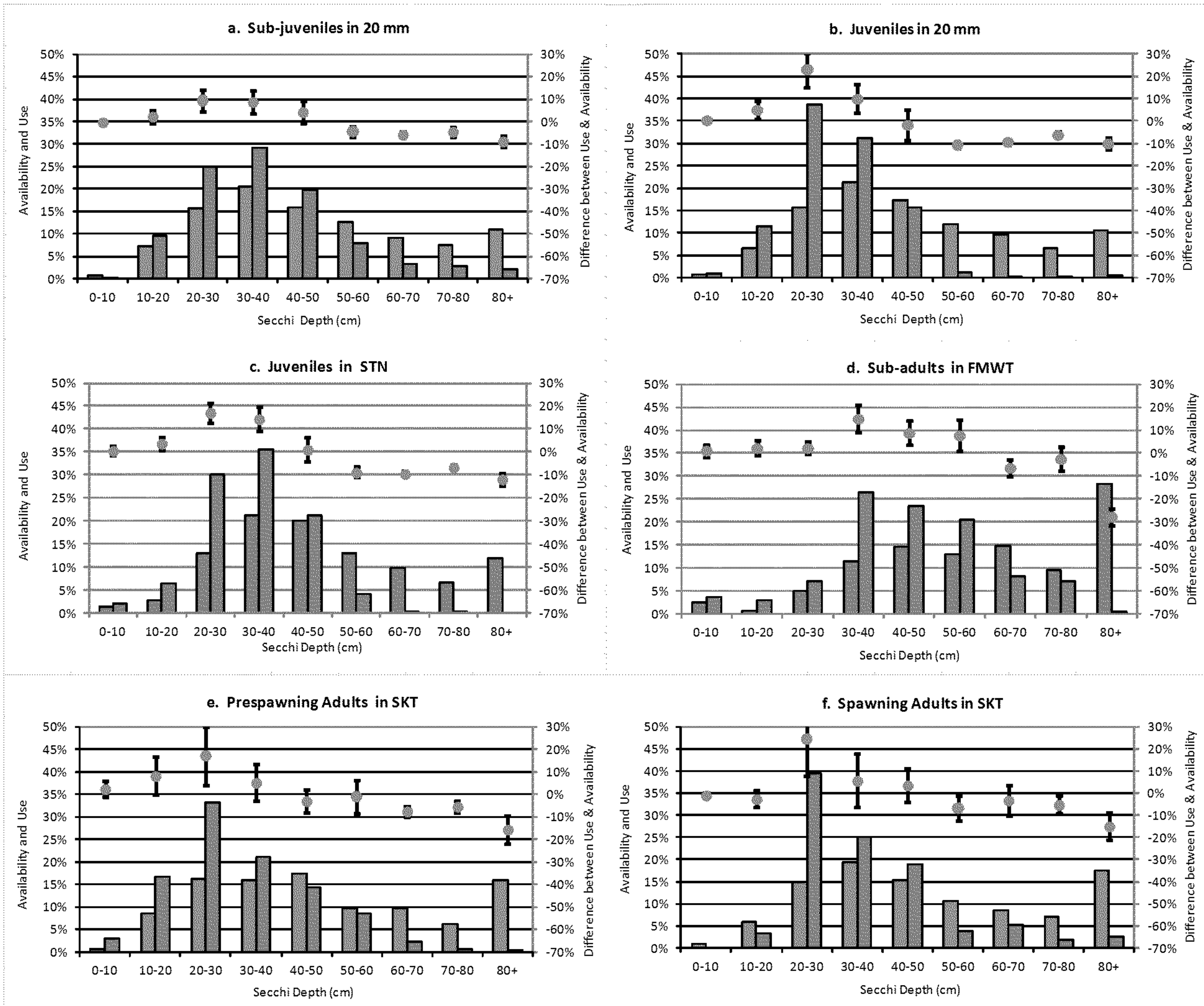

Figure 2. Affinity analysis for water clarity (secchi depth in cm) by life stage. Graphs depict the relative availability of a secchi depth segment (blue columns) and the relative use of that segment (red columns). Green dots show the difference between the two columns. The error bars around the green dots show the 90% confidence interval.

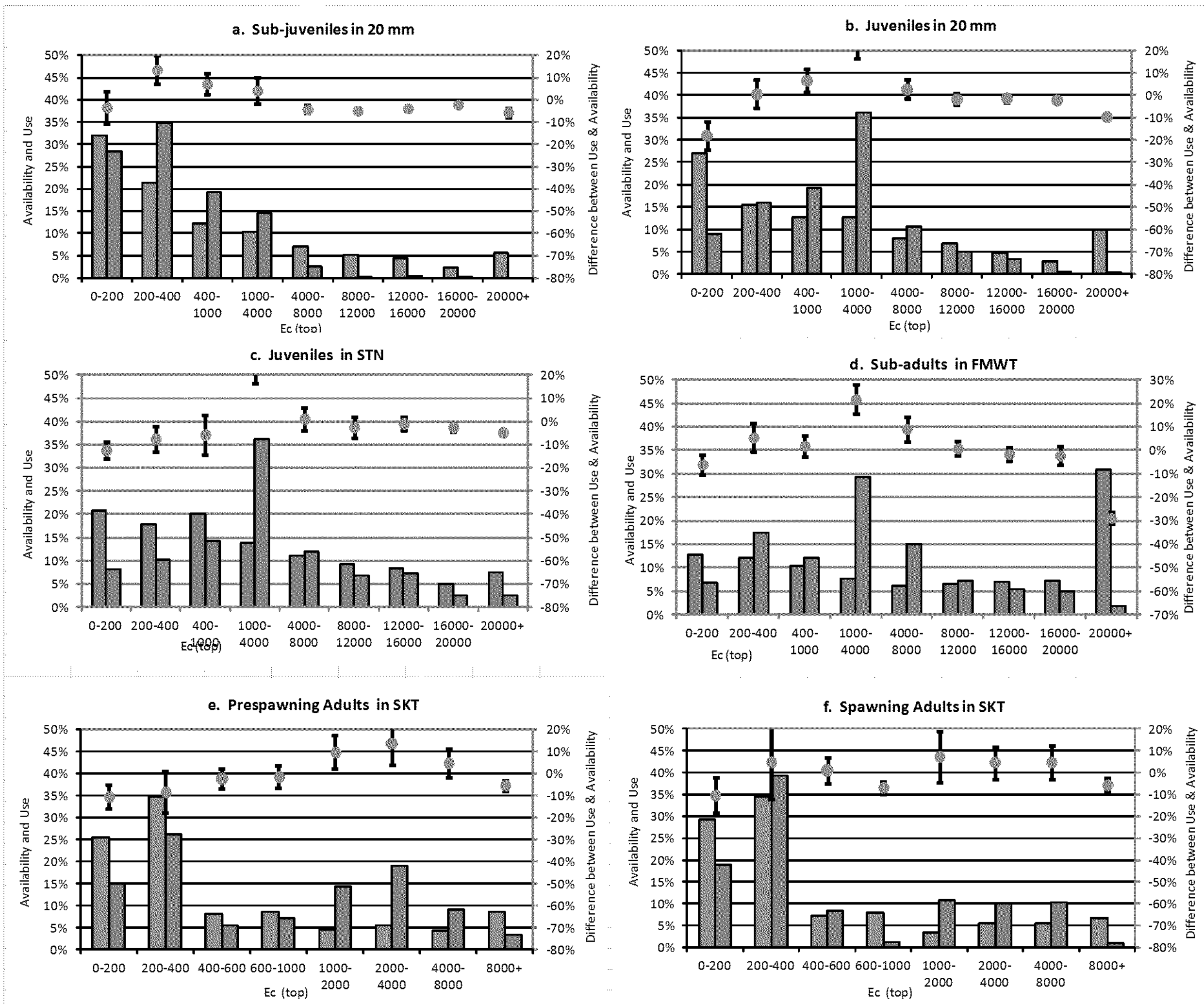

Figure 3. Affinity analysis for salinity (Ec) by life stage. Graphs depict the relative availability of a salinity segment (blue columns) and the relative use of that segment (red columns). Green dots show the difference between the two columns. The error bars around the green dots show the 90% confidence interval.

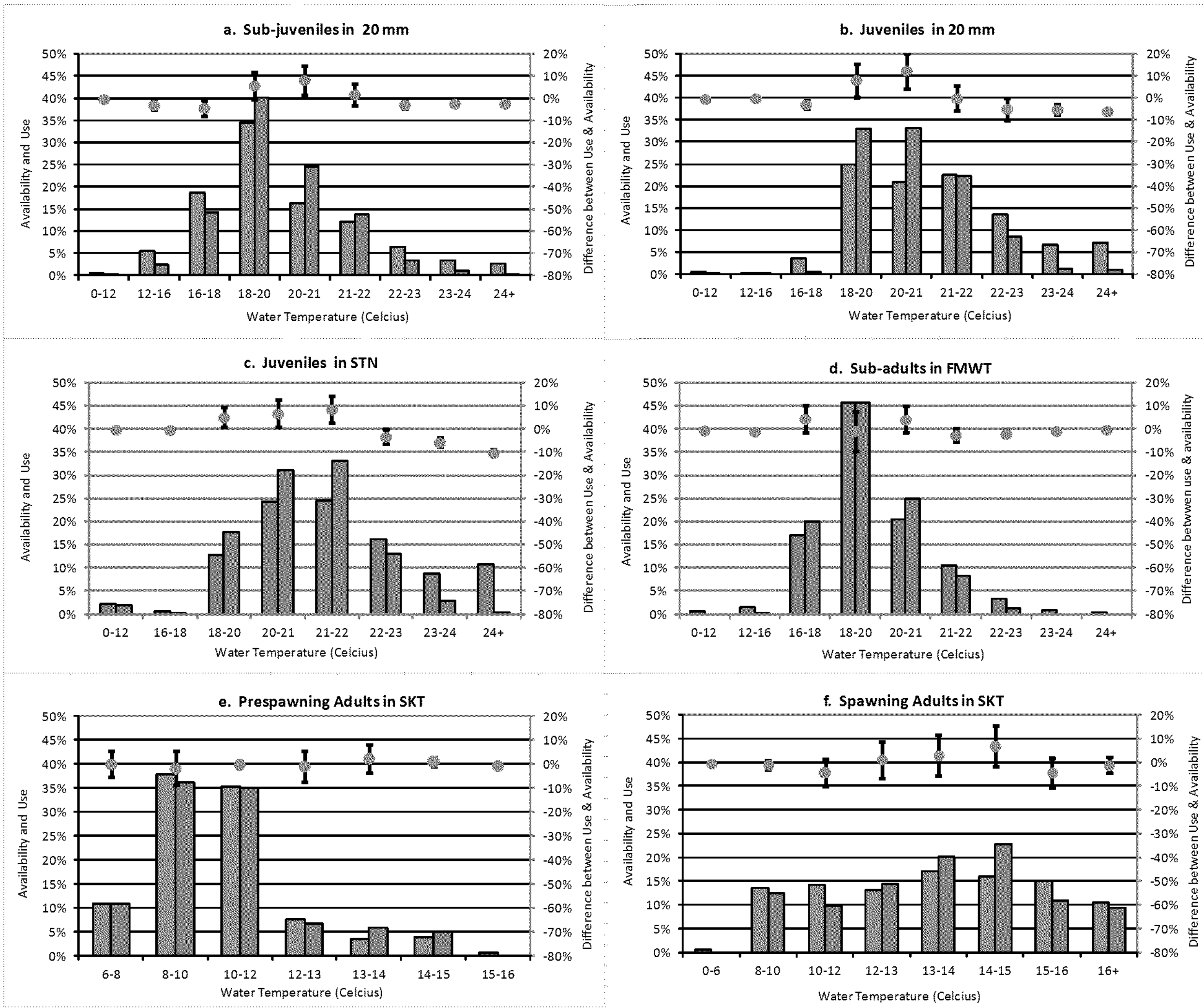

Figure 4. Affinity analysis for water temperature (Celcius) by life stage. Graphs depict the relative availability of a temperature segment (blue columns) and the relative use of that segment (red columns). Green dots show the difference between the two columns. The error bars around the green dots show the 90% confidence interval.

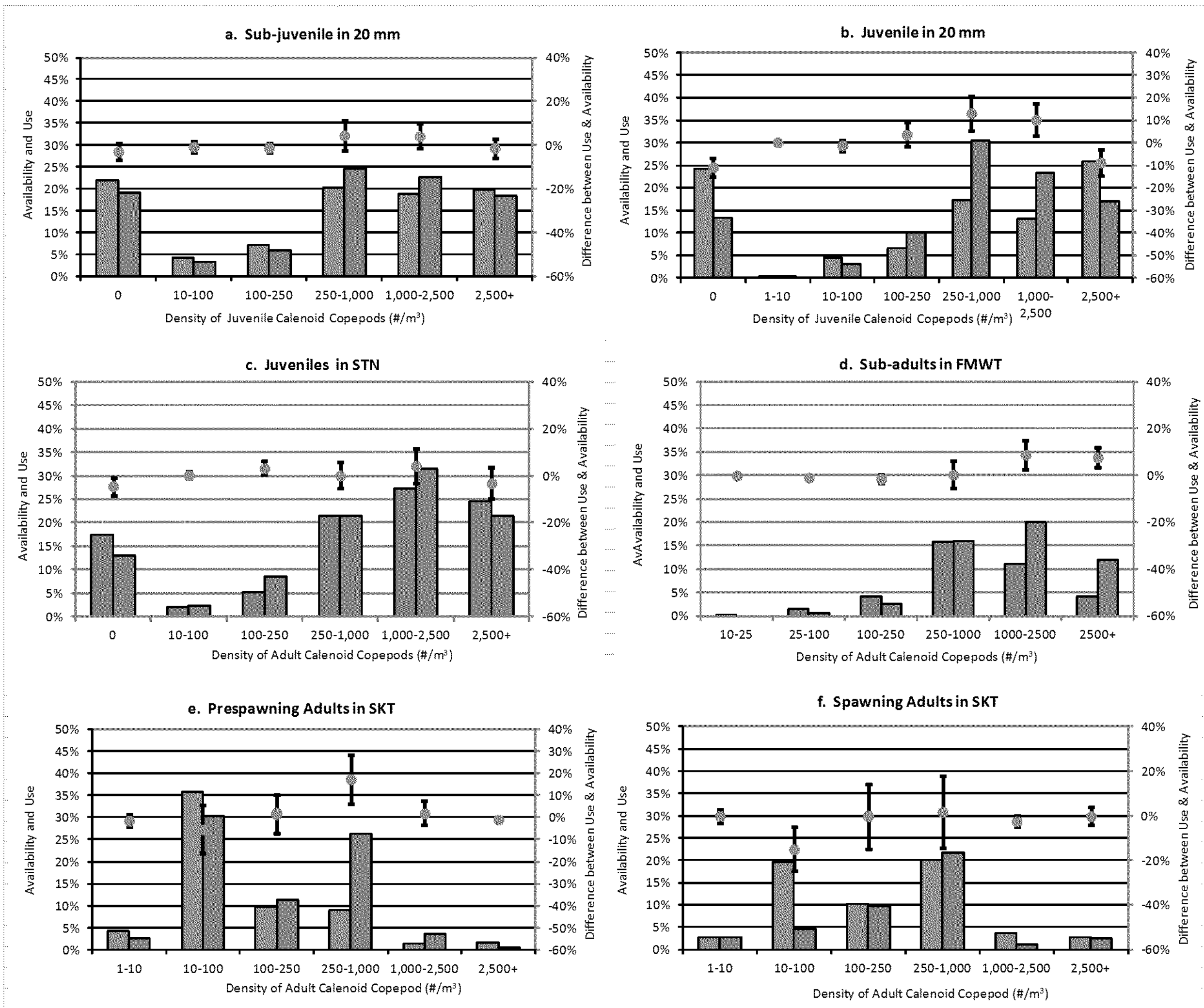

Figure 5. Affinity analysis for density of Calenoid Copepods by life stage. Graphs depict the relative availability of a Calenoid Copepod segment (blue columns) and the relative use of that segment (red columns). Green dots show the difference between the two columns. The error bars around the green dots show the 90% confidence interval.

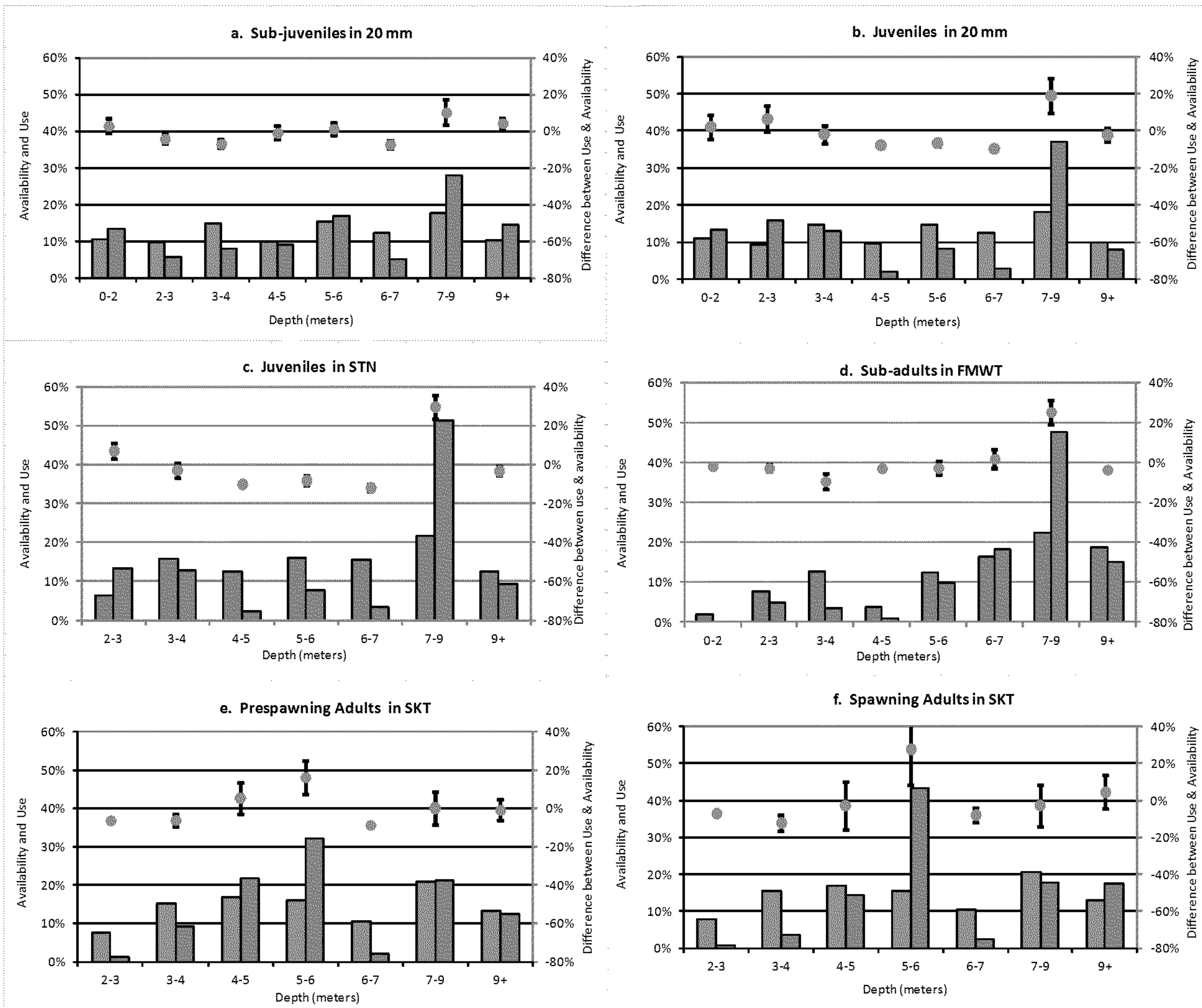

Figure 6. Affinity analysis for water depth (feet) by life stage. Graphs depict the relative availability of a depth segment (blue columns) and the relative use of that segment (red columns). Green dots show the difference between the two columns. The error bars around the green dots show the 90% confidence interval.

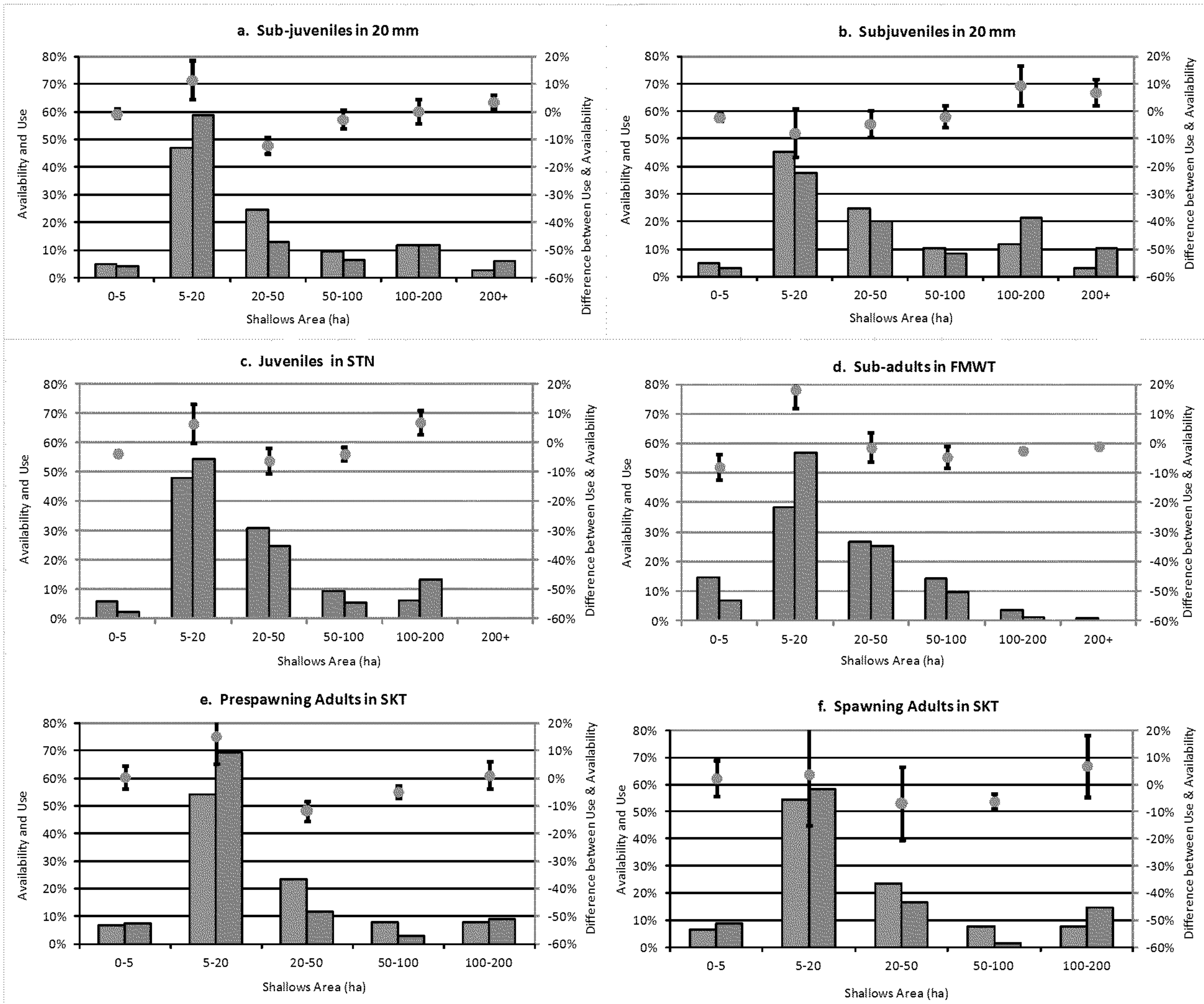

Figure 7. Affinity analysis for area of shallows (water less then 2 meters deep) by life stage. Graphs depict the relative availability of an area-of-shallows segment (blue columns) and the relative use of that segment (red columns). Green dots show the difference between the two columns. The error bars around the green dots show the 90% confidence interval.

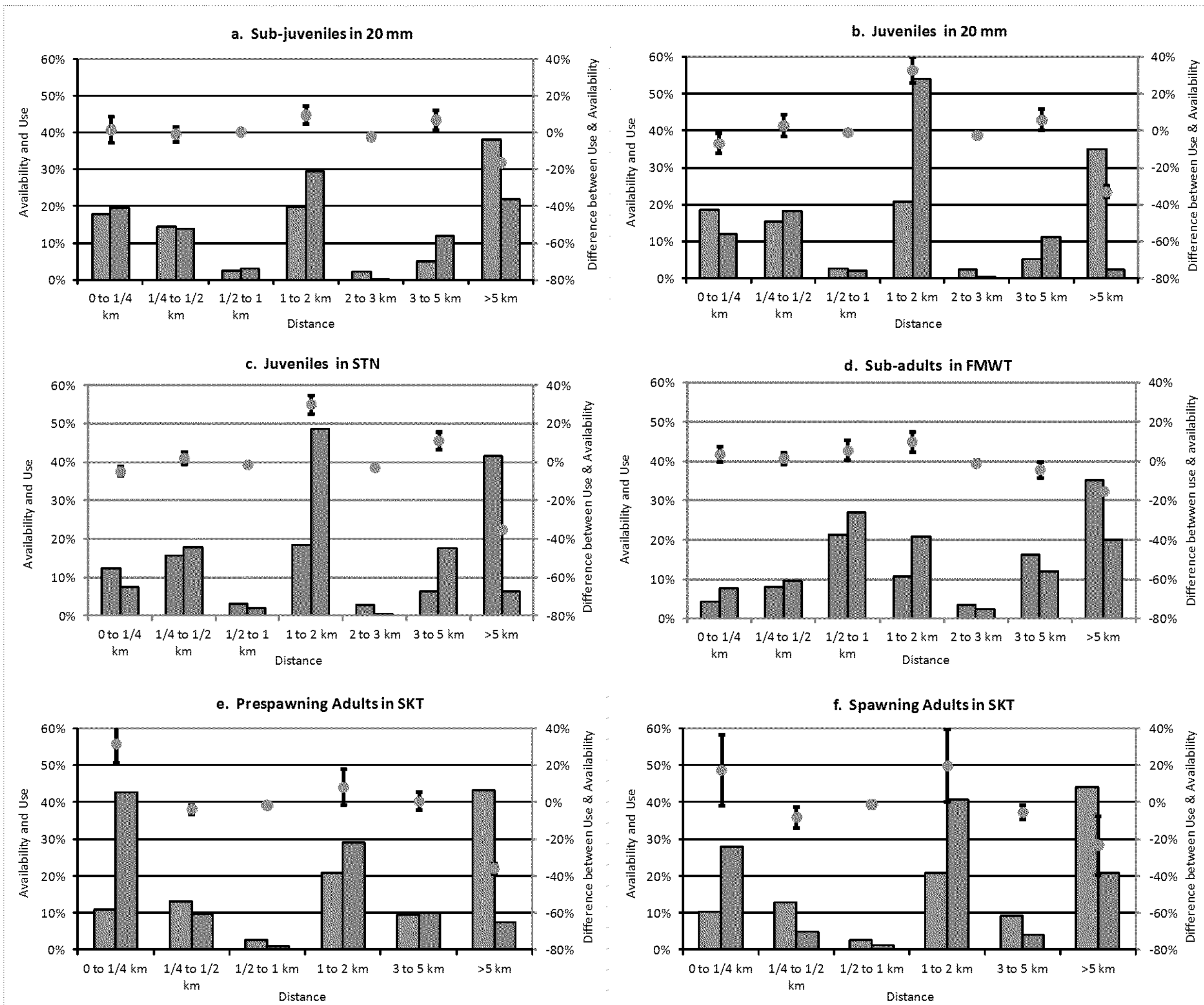

Figure 8. Affinity analysis for distance to large wetlands (wetlands >100ha) by life stage. Graphs depict the relative availability of a distance-to-wetlands segment (blue columns) and the relative use of that segment (red columns). Green dots show the difference between the two columns. The error bars around the green dots show the 90% confidence interval.

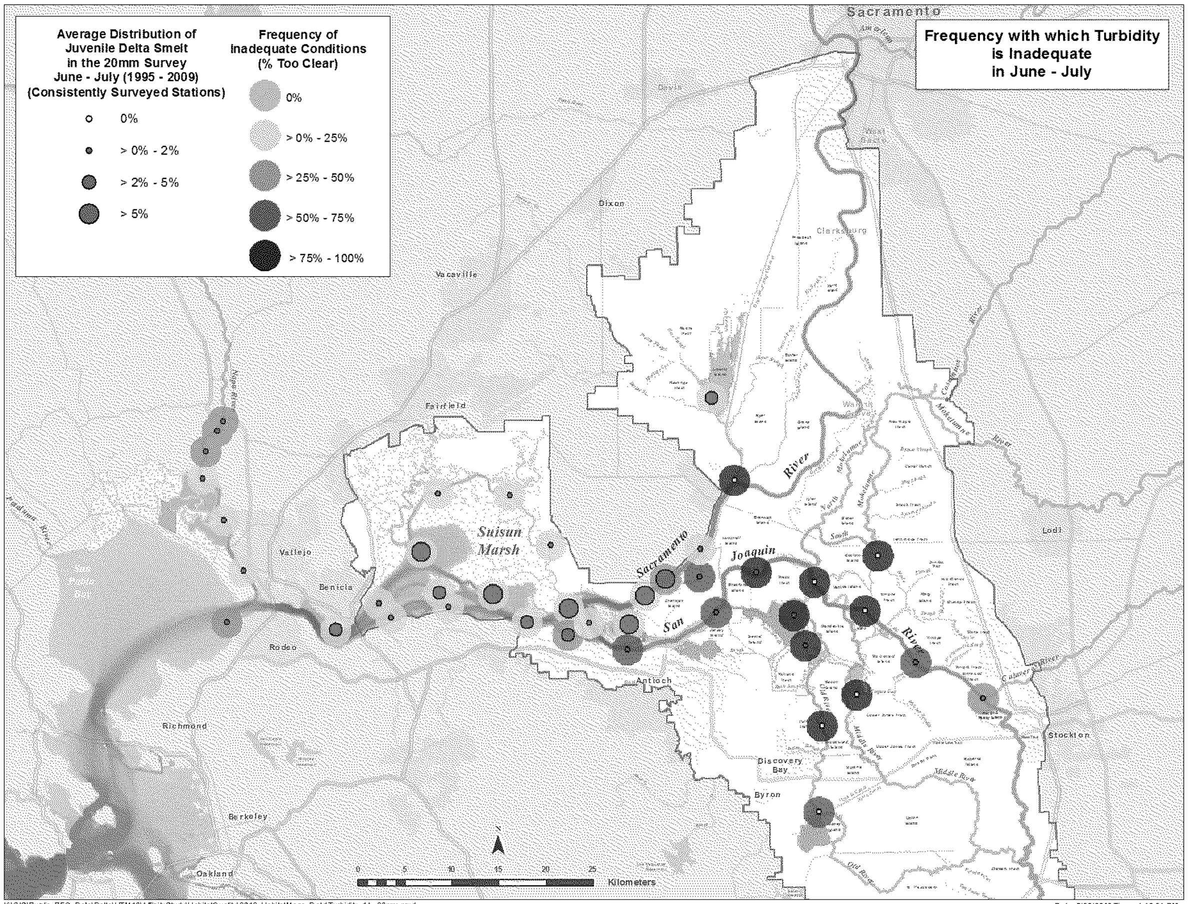

Figure 9. The distribution of juvenile delta smelt from 20mm trawl surveys and the frequency with which turbidity is inadequate (see Table 4). Gray circles indicate the across-years average of the percentage effort-corrected catch of juvenile delta smelt in the 20 mm Survey during June and July at each monitoring station.

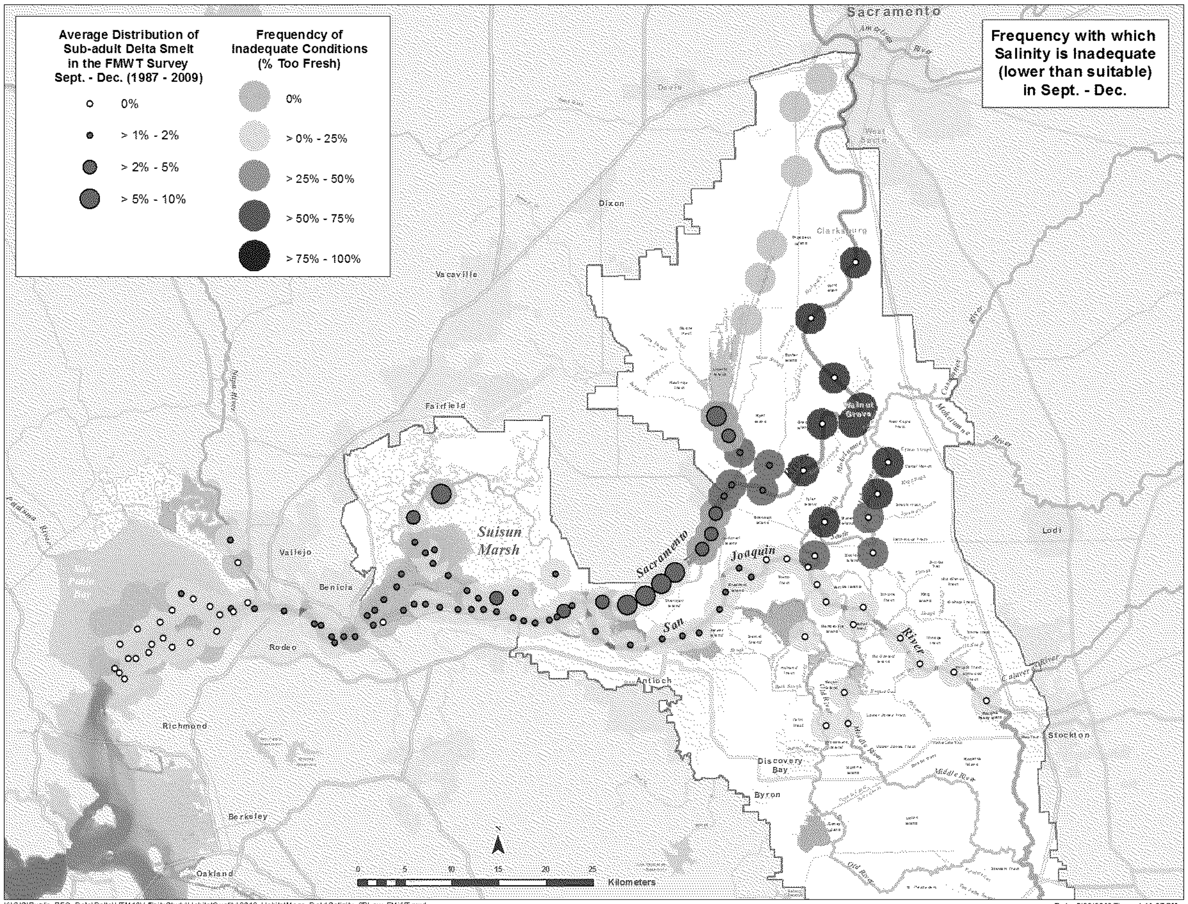

Figure 10. The distribution of delta smelt from the Fall Midwater Trawl survey and the frequency with which salinity is inadequate, with salinity levels too low (see Table 4). Gray circles indicate the across-years average of the percentage of the effort-corrected catch of sub-adult delta smelt in the Fall Midwater Trawl Survey from September through December at each monitoring station.

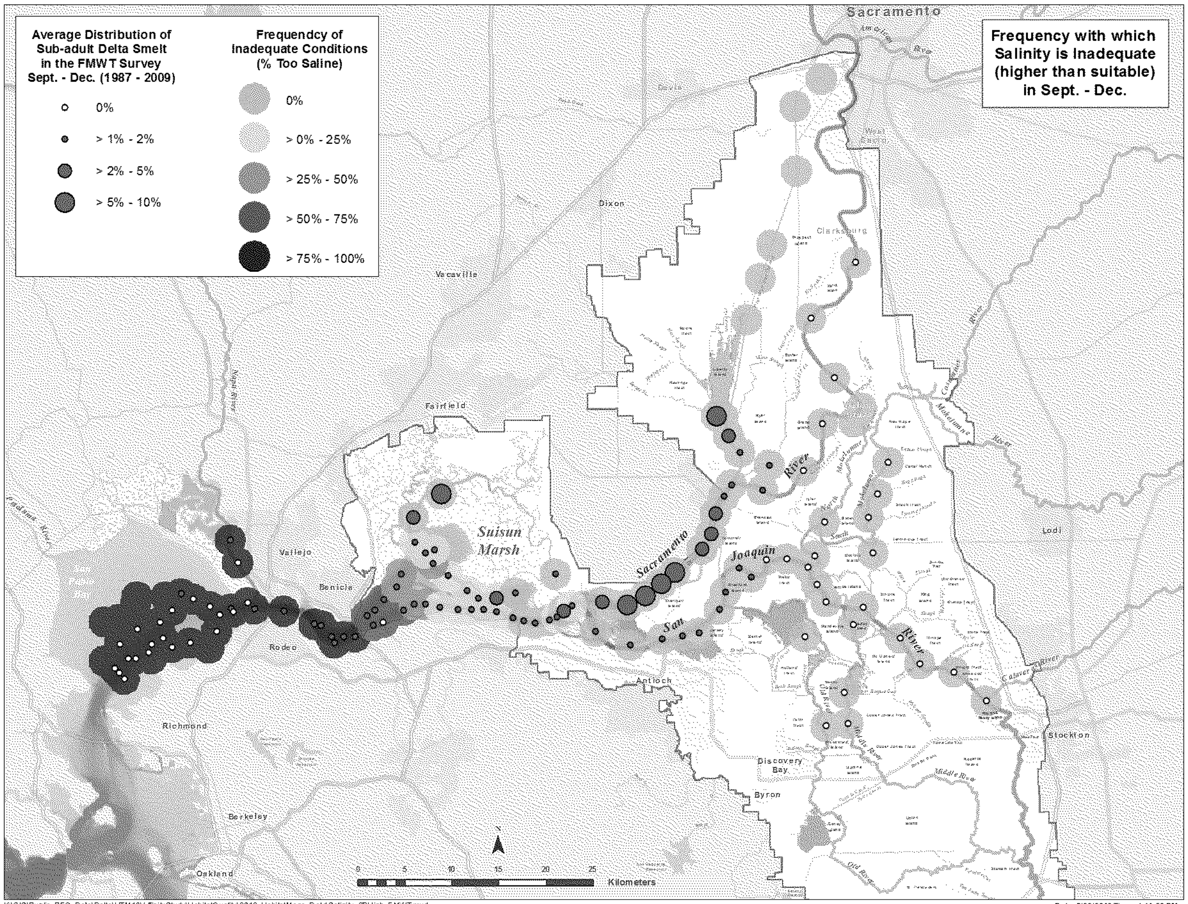

Figure 11. The distribution of delta smelt from the Fall Midwater Trawl survey and the frequency in which salinity is inadequate, with salinity too high (Table 4). Gray circles indicate the across-years average of the percentage effort-corrected catch of sub-adult delta smelt in the Fall Midwater Trawl Survey from September through December at each monitoring station.

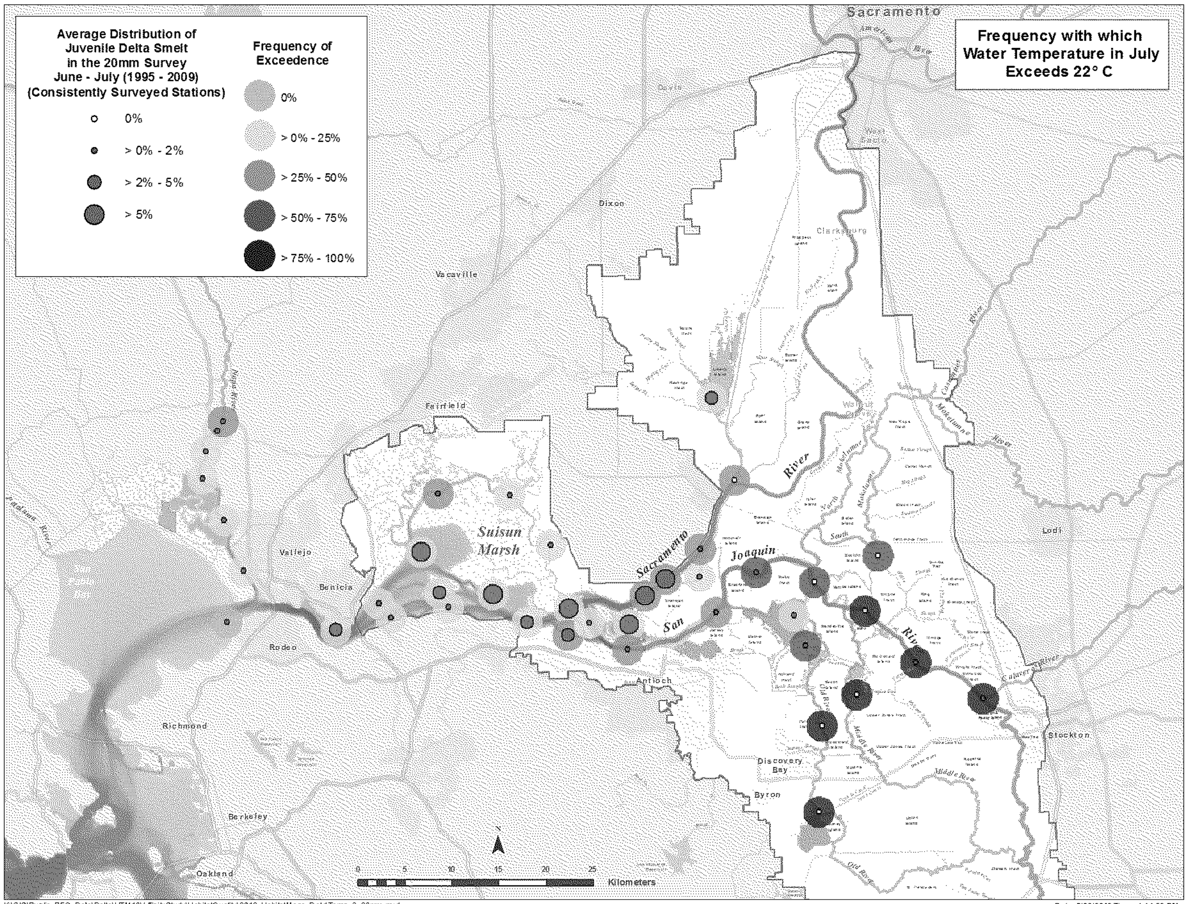

Figure 12. The distribution of delta smelt from the 20mm trawl survey and the frequency with which water temperature in July exceeds the 22-degree C threshold. Gray circles indicate the across-years average of the percentage effort-corrected catch of juvenile delta smelt in the 20 mm survey during June and July at each monitoring station.

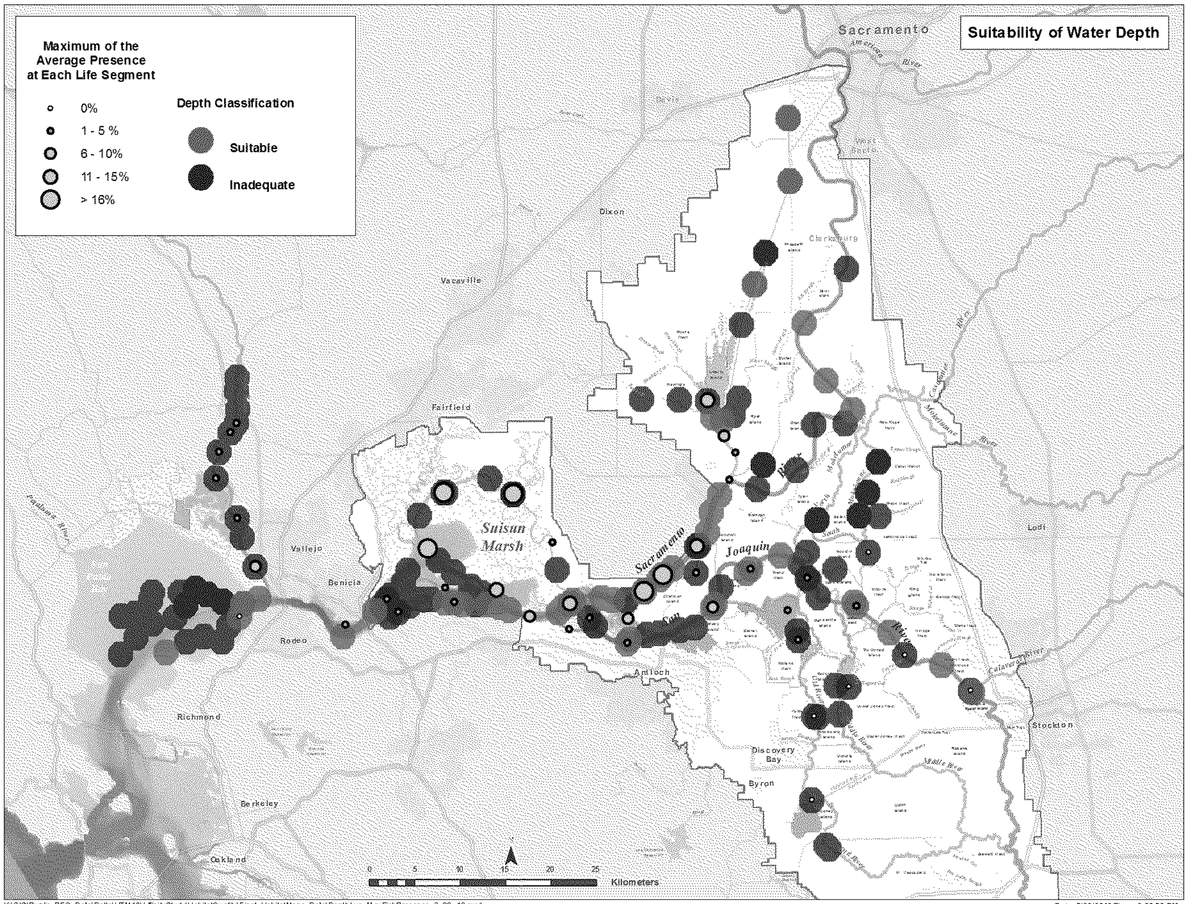

Figure 13. The maximum average presence of each of several life stages of delta smelt (from multiple trawl surveys) and the suitability of proximate water depth. Gray circles indicate the across-years average of the maximum percentage of the effort-corrected catch of delta smelt in any survey at each monitoring station. The colored circles indicate the suitability of average water depth at each station as classified in Table 4.

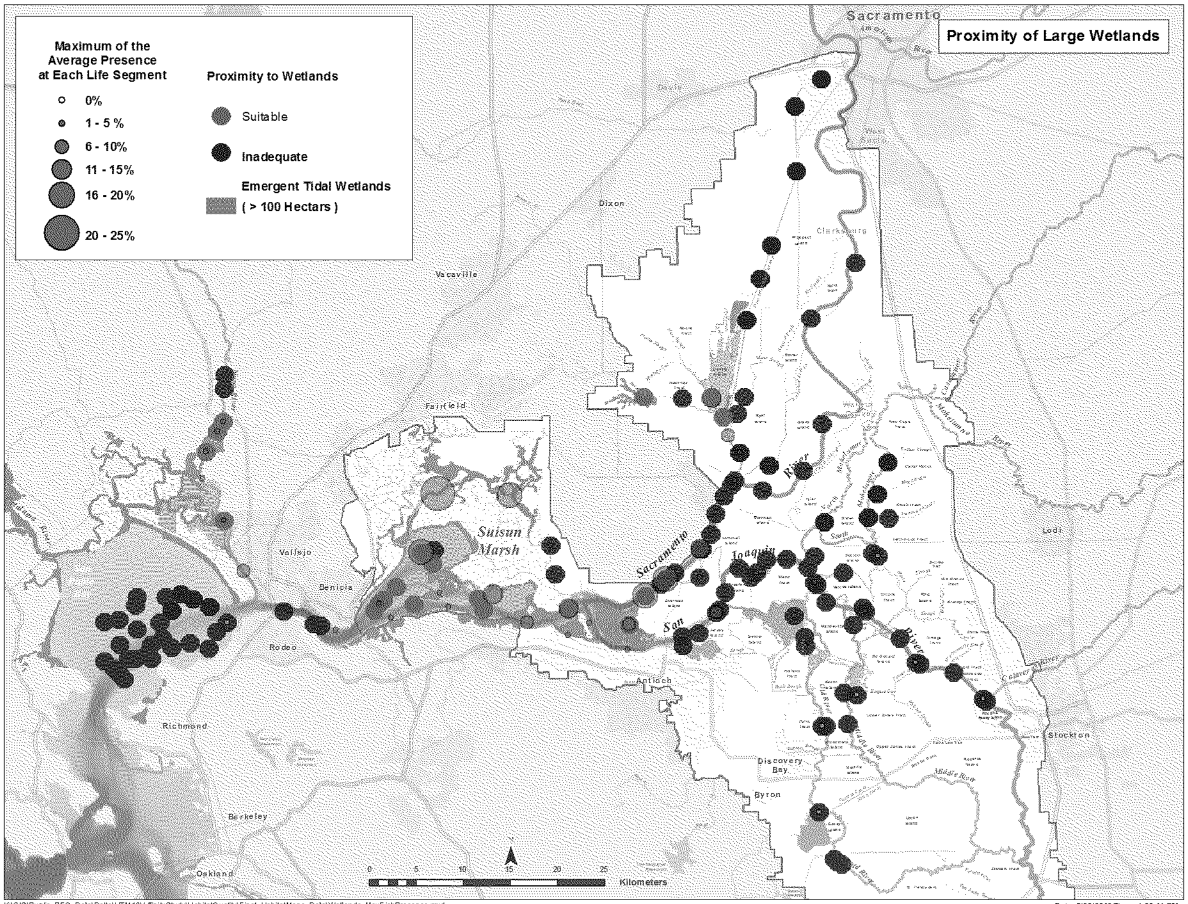

Figure 14. Maximum average presence of multiple delta smelt life stages at trawl survey stations in relation to station distance from wetlands greater than 100 hectares in extent. Gray circles indicate the across-years average of the maximum percentage effort-corrected catch of delta smelt in any IEP survey at each monitoring station. The colored circles indicate the suitability of the proximity of wetlands to each station as classified in Table 4.

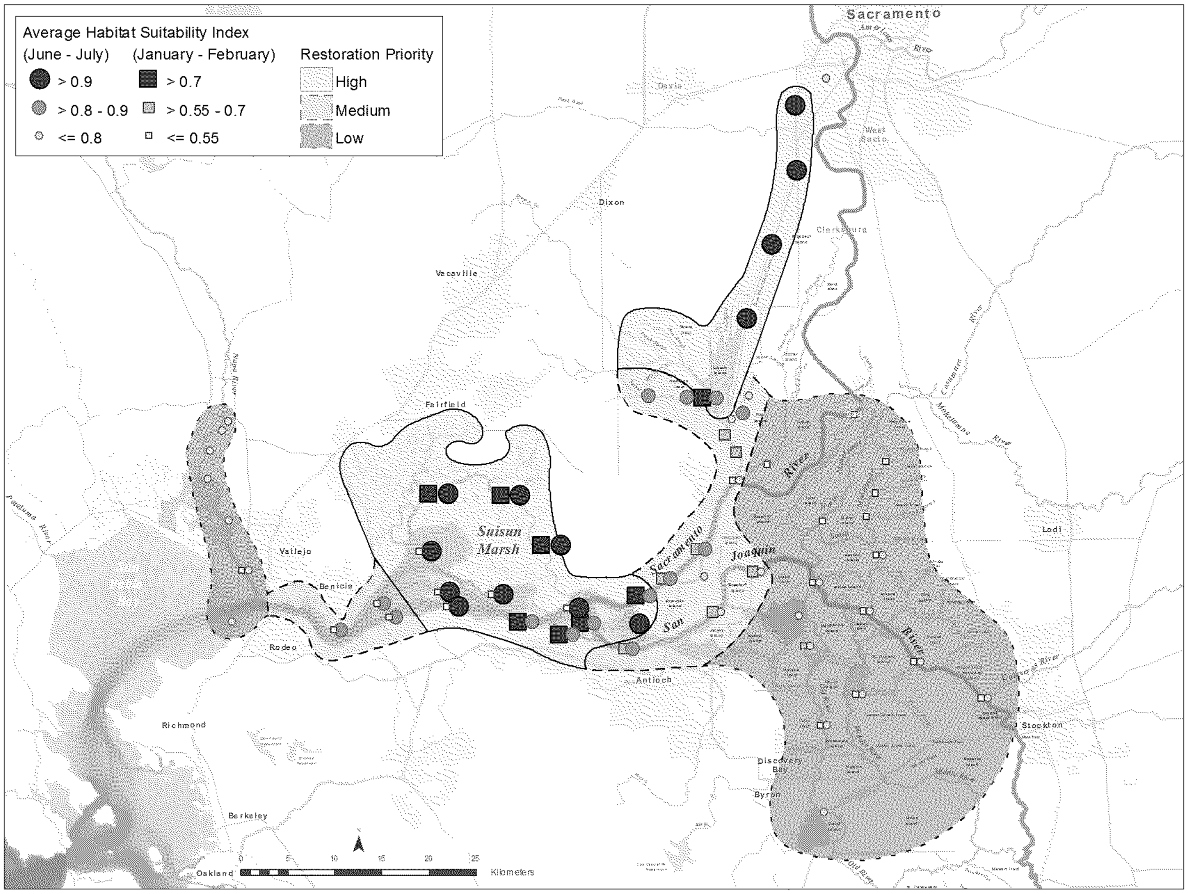

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Figure 15. Aggregated suitability for turbidity, salinity, and temperature at Spring Kodiak Monitoring Stations averaged for January and February and 20 mm Monitoring Stations averaged for June and July. The larger, darker symbols represent those stations with higher average weighted habitat suitability index values derived from these three attributes. Areas designated as high priority for restoration (light blue) contain stations with habitat suitability index values in the upper quartile in either survey. Areas designated as medium priority for restoration (tan) contain stations in the second highest quartile in either survey. Areas designated as low priority (grey) contain stations with habitat suitability index values below the median in both surveys.

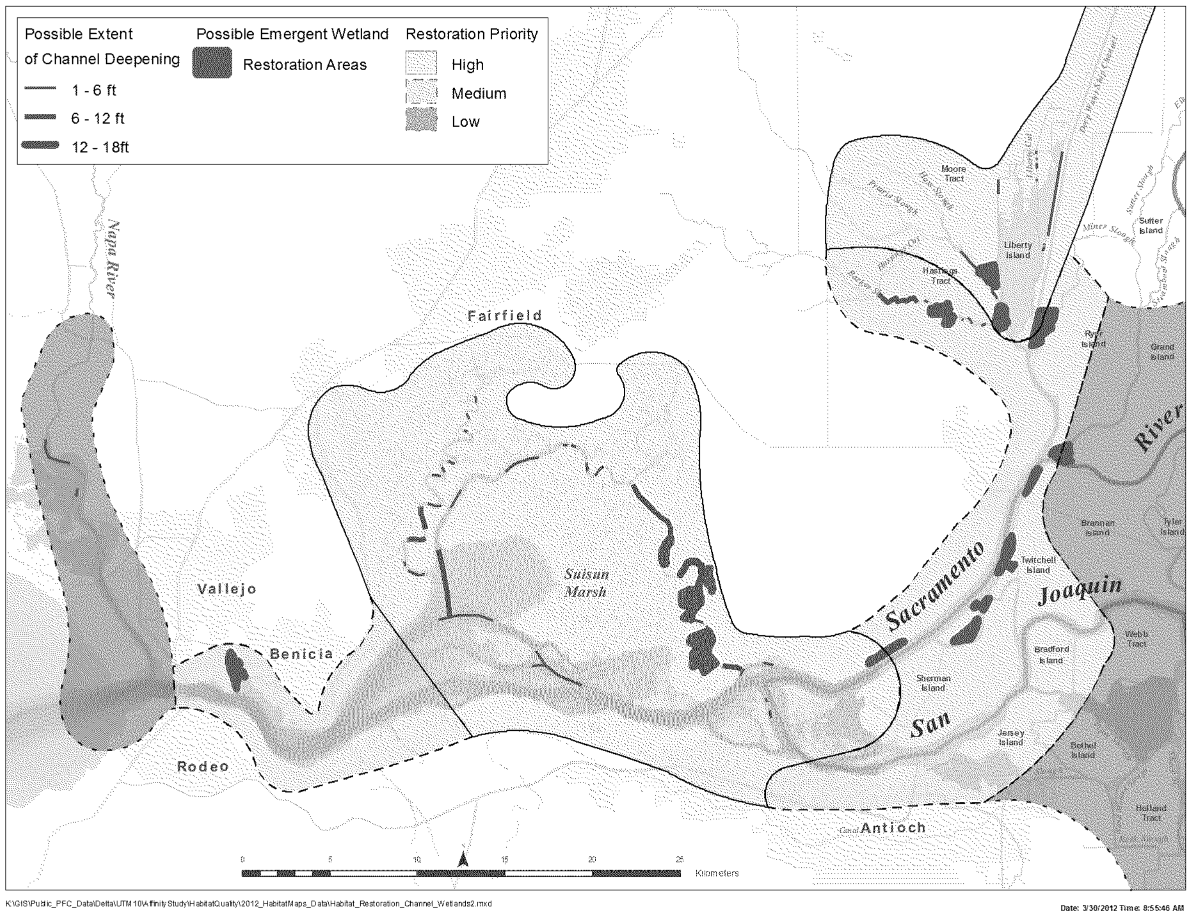

Figure 16. Candidate areas for channel modification and restoration of tidal emergent wetlands. The locations include sites for which other environmental variables are frequently within suitable ranges. Red-tone channel reaches (and other watercourses) are target areas for channel-deepening efforts designed to make local conditions for delta smelt suitable as habitat. The locations for wetlands restoration are sites for which other environmental variables are frequently within suitable ranges, within the current range of delta smelt, close to sea level, and are close to deep-water channel circumstances.